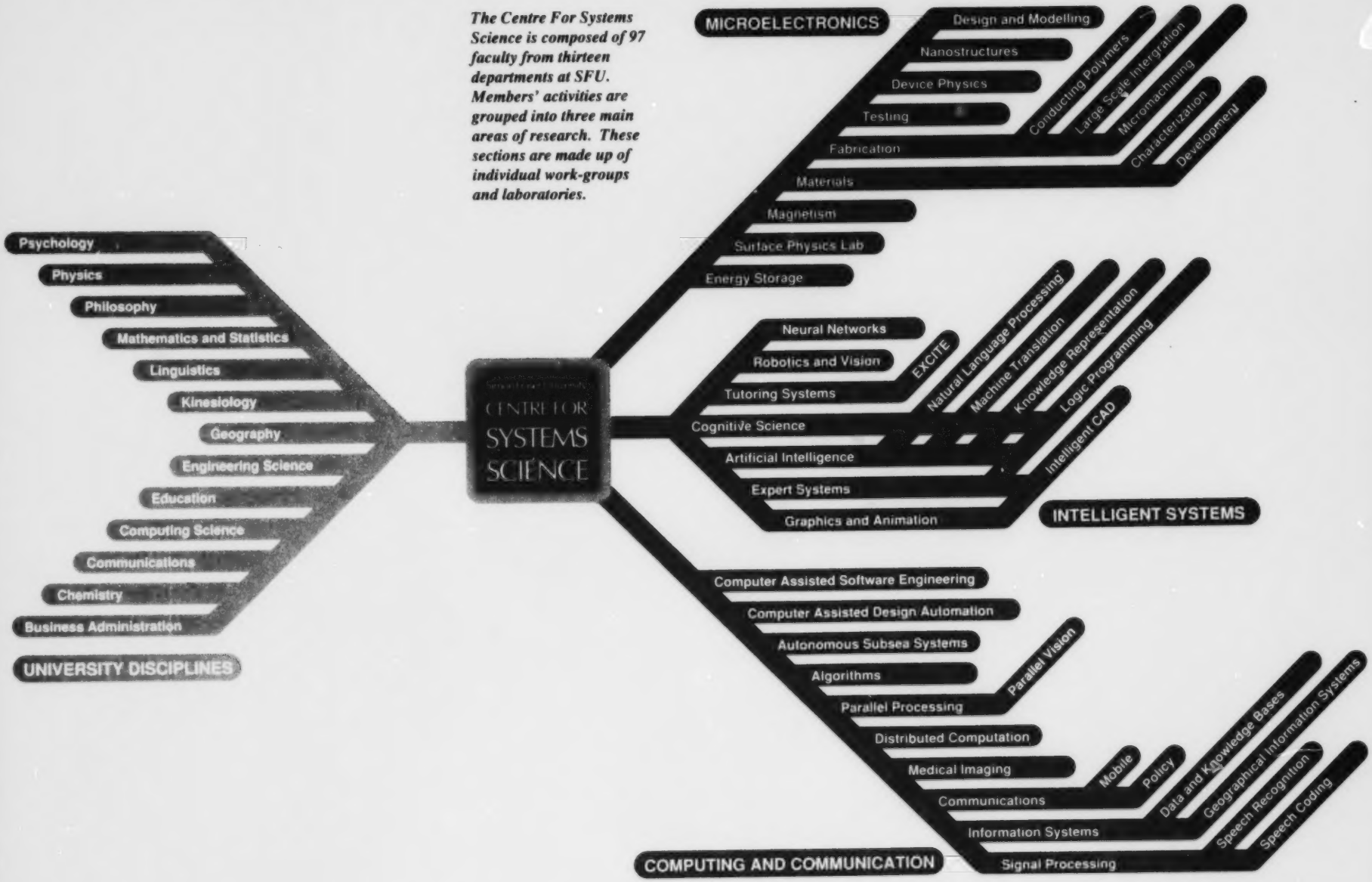
# Research Review 2

Simon Fraser University

# CENTRE FOR SYSTEMS SCIENCE


The Centre For Systems Science is composed of 97 faculty from thirteen departments at SFU. Members' activities are grouped into three main areas of research. These sections are made up of individual work-groups and laboratories.
MICROELECTRONICS
Design and Modelling
Nanostructures
Device Physics
Testing
Fabrication
Materials
Magnetism
Surface Physics Lab
Energy Storage
Conducting Polymers
Large Scale Intergration
Micromachining
Characterization
Development
Psychology
Physics
Philosophy
Mathematics and Statistics
Linguistics
Kinesiology
Geography
Engineering Science
Education
Computing Science
Communications
Chemistry
Business Administration
UNIVERSITY DISCIPLINES
CENTRE FOR SYSTEMS SCIENCE
Neural Networks
Robotics and Vision
Tutoring Systems
Cognitive Science
Artificial Intelligence
Expert Systems
Graphics and Animation
EXCITE
Natural Language Processing
Machine Translation
Knowledge Representation
Logic Programming
Intelligent CAD
INTELLIGENT SYSTEMS
Computer Assisted Software Engineering
Computer Assisted Design Automation
Autonomous Subsea Systems
Algorithms
Parallel Processing
Distributed Computation
Medical Imaging
Communications
Information Systems
Signal Processing
Parallel Vision
Mobile
Policy
Data and Knowledge Bases
Geographical Information Systems
Speech Recognition
Speech Coding
COMPUTING AND COMMUNICATION

# Research Review2

92-05384/

Simon Fraser University

CENTRE FOR SYSTEMS SCIENCE

Reporting on research
conducted by the
Centre for Systems Science
at Simon Fraser University
Burnaby, British Columbia

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Printed at SFU, March 1992

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The Centre For Systems Science is funded by the British Columbia Provincial Fund For Excellence in Education.

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# Introduction

### What is Systems Science?

Many research endeavours benefit from a multi-disciplinary approach. The process of vision, for example, can be studied physiologically to determine how light is detected by the eye. Engineers can use this knowledge to make a mechanical eye. Unfortunately this device would not be able to interpret images. Mathematicians may be able to show how large amounts of visual data can be restructured graphically for easier representation inside a computer, but they still cannot say how the mind recognizes things. Psychologists can help with this, but the answer might lie in the domain of philosophy or fine arts. In other words, human vision is not a simple task, but a complex system that can only be fully comprehended by a team of researchers.

Systems Science also recognizes that many technological solutions involve complex interactions. An efficient mobile communications system requires engineers to develop the hardware as well as regulatory specialists to resolve complicated policy issues.

### What is the CSS and Why does it exist?

The Centre for Systems Science acts as the local arm of the B.C. Advanced Systems Institute (ASI) at Simon Fraser University. ASI was established jointly by the Canadian and British Columbia governments in 1986 as a centre of excellence for integrated research and educational activity in advanced systems including the fields of computing science, microelectronics, systems design, artificial intelligence, robotics and aerospace. (ASI is represented at the University of British Columbia by CICSR while the University of Victoria has the LACIR.) Two particularly important roles of the CSS are to encourage associations across departmental boundaries and to ensure the application of SFU research in B.C. Industries. The CSS also encourages basic research. All these features attract funding and human resources to the University. Since its inception, the CSS has brought in over four million dollars in research funding. In addition, it has attracted dozens of world-class experts who have visited or taken positions at SFU.

### Where is the CSS?

The CSS main office is located in room 9801 of the Applied Sciences building at the east end of the Simon Fraser University campus on Burnaby Mountain near Vancouver, B.C. Most of the major CSS laboratories and work-groups can be found in the Applied Sciences building, while others are scattered around the campus in departments such as Physics, Kinesiology, or Geography.

### Who is in the CSS?

At present the CSS is composed of 97 SFU faculty members, their associated graduate students, research assistants and technical staff. Members are predominantly from Computing Science and Engineering Science, but many represent other departments like Mathematics, Physics, Kinesiology, Linguistics, Education, Geography, Philosophy, Communications and Psychology. (See the Organization Chart inside the front cover.)

### What can the CSS do for you?

For members, the CSS provides either direct funding or the opportunity for:

- Scholarships, including:
  - -ASI Fellowships
  - -Visiting Fellowships
  - -Graduate Students
  - -Top-up grants
- Workshops, Symposia and Conferences
- Equipment
- Travel
- Faculty Positions
- Matching Grants
- Employing Research Assistants and Technicians

The CSS can also help members to:

- Write better research grant proposals
- Leverage grant money from outside organizations
- Bring visiting faculty, researchers, and guest speakers to SFU

For the public and the SFU community, the CSS:

- Attracts top-notch graduate students
- Attracts high profile researchers
- Publicizes innovative research at SFU
- Provides public lectures, symposia and conferences

### Who can be a member and how does one join?

Any systems science oriented SFU faculty member can join the CSS. If you are interested, please call the office to arrange an interview and fill out an application.

### Want to find out more?

Call or write for brochures that give more detail on the three main research areas of the CSS: Computers and Communication, Intelligent Systems, and Microelectronics. Leaflets describing individual work-groups and laboratories are also available. The CSS publishes *Update*, a monthly newsletter that contains announcements and profiles of CSS researchers. Ask us to put you on the mailing list. Drop in to the CSS office anytime to get new ideas for research funding and to learn about upcoming seminars and visiting scholars. A list of coming events, scholarships, grants, and visitors will be maintained on the bulletin board outside the office.

# Letter From the Director

*Our role is to create an environment that encourages long-term research and multidisciplinary associations.*

Albert Einstein once said, "There exists a passion for comprehension, just as there exists a passion for music. That passion is rather common in children, but gets lost in most people later on." The Centre for Systems Science (CSS) is now five years old—an adult in most University settings, however, at times it seems as though we have always been children.

From the inception of the British Columbia Advanced Systems Institute (ASI) in 1986 and the subsequent Provincial Funds for Excellence in Education (FEE) which sired the Centre, CSS has attained or surpassed expectations which made it the top priority FEE activity of Simon Fraser University. We can look back with pride for our role as research facilitator for advanced systems at Simon Fraser, for leveraging millions of extra dollars of R&D funding, and for creating an environment that encourages long term research and more multidisciplinary faculty associations.

Since publication of our last review more than two years ago, CSS has grown to 97 members. In part, such growth reflects the multidisciplinary interests of nearly 20% of SFU's faculty. Many new faculty who have become members come from outside of Applied Sciences, the traditional home for CSS. As CSS members continue to win ASI Fellowships and other honours, members from Science and Arts have been counted into this fraternity of scholars, Fellowship winners, etc. In future, I'm sure, we will count among them members from Education and Business as well.

During our formative years, CSS experimented with a variety of methods intended to promote SFU advanced systems research and several have evolved and stabilized into the fine programs we operate for the advantage of our members and SFU. Our *Matching Grants* program appears to increase CSS members chances for external grants by more than a factor of two, and has returned to SFU an average of $4.50 for every $1 of CSS funds. Our *Strategic Initiatives* are too new to say anything definitive, but it is heartening to note that early strategic initiative winners are now applying for larger, targeted grants and contracts from external agencies. Due to internal funding problems, the third year of our *Sun Microsystems Agreement/ Laboratory Renewal* was not honoured. Nonetheless, we anticipate renewal of CSS laboratories will accelerate this year without undue consequence. *Graduate Student Support* was, I'm sure, greatly appreciated by member departments who were able to attract a few extra students. As always, our *Opportunities* program gave us flexibility to "jump-start" new faculty, aid members in small but important ways expeditiously, and take advantage of opportunities.

CSS played an instrumental role in helping to negotiate final arrangements in the multi-million dollar PRECARN sponsored Intelligent Graphics Interface project initiated by CSS members John Dill, Bill Havens, and John Dickinson. CSS members participate and, in some cases lead, in three of the Federal Networks of Centres of Excellence, resulting in millions of dollars of research funding. The CSS has been instrumental in obtaining several NSERC Industrial Chairs, in part through Strategic Initiatives Funding to CSS member and Chairholder Mike Thewalt (Physics), and in writing the proposal and marshalling B.C. industrial and agency (ASI and B. C. Science Council) support for the dual chairs Program in Applied Artificial Intelligence (Computing Science and Engineering Science). There are so many items left unreported, but then read this Research Review for some of them.

I take this opportunity to record my appreciation to the staff of the Centre, whose hard work and dedication have helped to produce the good work mentioned above—and more. I would also like to thank all of you who have contributed to the content and production of this review. Finally, I thank all of you who have helped to make the CSS what it is today.

Are we "becoming an adult" ever mindful of Einstein's admonishment? Take heart, for as Picasso once mused, "It takes a long time to become young."

Nick Cercone

# The Management of Technology

*A bewildering assortment of new high tech products arrive in today's market place every year. Production systems have been greatly refined. But the product formulation stage—deciding what products to make with the new technologies—has become increasingly complex. A new joint SFU/Waterloo Chair in Management of Technological Change will be filled by Paul Guild. Dr. Guild will address these and other problems in the fast-paced world of high-tech product development and production.*

"It was obvious from the beginning that he was not your average scruffy psych student," says Don George, SFU Dean of Applied Science, describing his first meeting with the young Paul Guild at Carleton University in 1973. Paul was fascinated with the psychological problems of desk-to-desk audio-video conferencing. He asked Don, then Dean of Engineering at Carleton, if he could work in the special telecommunications laboratory they called the "wired city".

Intelligent and very gentle despite his size—an imposing 6'5"—Paul took a leadership role in the project and developed lasting social ties with Don. Now, 18 years later with a doctorate from Oxford and over a decade of experience in the communications industry, he is the first professor to assume the new joint SFU/Waterloo Chair in the Management of Technological Change. The five-year, $1,200,000 program is being funded by NSERC (Natural Sciences and Engineering Research Council), SSHRC (Social Sciences and Health Research Council), SFU, U of W, BC Tel, and BNR (Bell Northern Research). Its goal: to find ways to reduce the time it takes to formulate ideas for marketable high-tech products and services. "Although we have seen remarkable reductions in the time it takes to develop and deploy new products," says Guild, "the duration of the crucial product formulation phase has actually *increased*." The major hurdle for companies in today's product development cycle is to answer the question: "What products should we create with all this new technology?"

CSS members in particular are expected to benefit from Dr. Guild's research. Don George: "Personally I would like to see this activity be at the front and centre of the CSS. More work needs to be done on the interaction between people and machines. At the moment it seems that technology drives technology and it's almost happenstance. We have to explore issues of the human needs behind technology." Research in this area could ultimately help industry focus on better products, while helping governments formulate policies to deal with technology's effect on society.

***Paul Guild in his new office at SFU Harbour Centre Campus.***

While working at BNR, Paul helped form the company's first Technology Management Group. He helped pioneer a new method called *Champions of Innovation*. "Its purpose was to create focus in amongst design teams," says Paul. "For example, we might have a team consisting of a mechanical engineer, an industrial designer, a human factors specialist, a microelectronics engineer, a mechanical packaging designer, a safety engineer and some marketing people. We would all pile into an airplane and spend a week touring California companies having pre-arranged meetings with champions of innovation. Typically, these people are so fired up about what they do that it's contagious. And they don't mind spending time with us. In some cases they love it because we've assembled our best people, so we're bringing a lot of intellectual and inspirational power to them. The result of the whole exercise is that you get the design team to more quickly express their *own* ideas for innovation, to have a stronger business sense *as well as* a stronger technological sense that the project will work."

With such an exciting job, why would Dr. Guild want to return to academia? "In industry

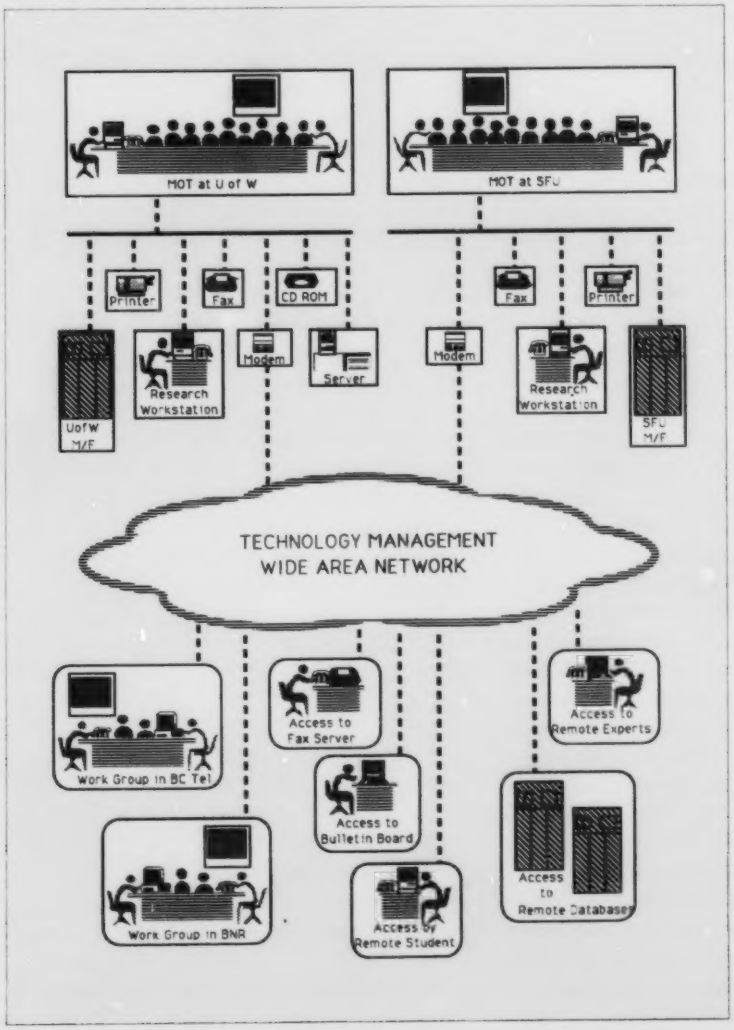
Reprinted from CSS Update newsletter Vol. 3, No. 1, Jan. 91

*"You get the design team to quickly express their own ideas for the innovation, to have a stronger business sense as well as a stronger technological sense that the project will work."*

you have an incredible amount of relevance but not enough think time," says Paul. "For me, taking the university chair is a trade-off to have time to think about theories but to also use the theories in real design teams." A few of the theoretical and empirical ideas that Paul would like to explore in his new position include:

- How design group creativity changes following exposure to innovators.
- Analysis of competition and competitive positioning by design teams.
- Identifying and overcoming barriers to change within design teams.
- Expanding the method to the service sector.

Both industry and academia are sure to benefit from research programs in the Management of Technology. In fact Paul's job is an experiment in education and communications technology. The chair is simultaneously held at two universities 4000 kilometres apart. Paul will spend part of the year in Waterloo, Ontario and the other part in Vancouver, B.C. His two offices (and eventually classrooms) will be connected by novel telecommunications technology that Paul calls an "audio-graphic link". "This networking experiment is important in our Canadian context because our population is so sparsely dispersed," says Paul. "We need ways to create viable distributed research environments, decreasing the isolation caused by the vast distances in our country." Some of the networking equipment was provided by Apple Canada.




***Management of Technology offices and classrooms at SFU and Waterloo will be heavily networked locally and over a wide area network like CAnet.***

The new Management of Technology chair is administered by CPROST (Centre for Policy Research on Science and Technology) which gets some funding from the CSS. SFU and Waterloo were chosen because of their strong links with industry, concentration on information technologies, outstanding co-op education programs, and shared trimester systems.

Paul's wife, Inta, and twin 5-year-olds, Emma and Jesse, will stay in Waterloo when he is teaching in Vancouver. "I regard this as a very challenging change in career," says Dr. Guild. If you are interested in the new program call Dr. Guild at (519) 888-4802.◊

# New Life Form Evolving

*Advances in computer technology have lead to realistic simulations of human movement. At SFU, one group of researchers has successfully commercialized a human figure animation system that can be used for dance choreography, sports analysis, and motion picture action scene planning. It can even help create human-like beings that exist only in the mind of a computer.*

Get ready. Virtual celebrities are coming—computer generated personalities as real as your favourite movie star but with as much physical body as Max Headroom. One virtual character named Lotta Desire already has a human agent who licenses her appearances in advertisements and films.

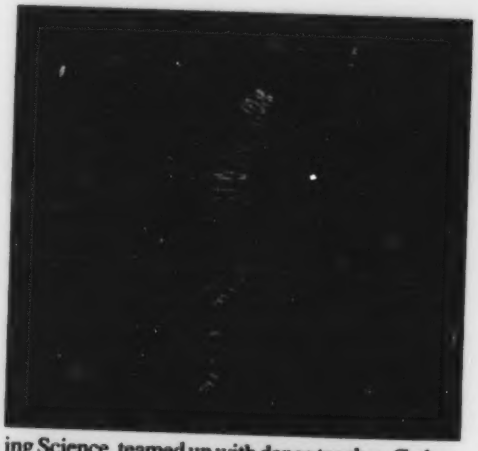
California venture capitalist Dean Hovey was on the lookout for software that could create such new life forms while attending a conference on Human Factors in Computing Systems in Seattle last May. "Our firm had targeted human body modelling software as an investment opportunity," says Hovey. Cash register bells must have been ringing in his mind as he watched a graduate student from SFU presenting a dance choreography software package called *COMPOSE*.

The grad student, Thecla Schiphorst, was having an "on" day. She finished her talk with a video showing six multicoloured computer animated human figures walking and jumping around a virtual stage to the tune of Patsy Cline's hit single, *Walkin' After Midnight*. The animation had been created in the CSS Graphics Lab at SFU. When it finished, the crowd of several hundred, having expected yet another human interface to an accounting system, cheered with delight to see a human interface to a human body. At least thirty people crowded around Thecla offstage.

"I was overwhelmed," she says. "People were handing me business cards, offering to fly up to Vancouver and inviting me out for breakfast, lunch and dinner." One of them was Dean Hovey.

Hovey visited SFU a few weeks later with Cole Larson, a Microsoft project manager in charge of multimedia applications in Windows 3.0. Hovey then went to MIT, Disney Studios and other places to evaluate the state of human animation software research. "I determined that there was currently not really anything like it in the world," says Hovey. "Cole and I brainstormed and decided to form a company called Kinetic Effects based on the SFU software." Larson left Microsoft to manage the new start-up venture.

The story of Kinetic Effects really began in 1985 when Tom Calvert who holds joint professorships in Kinesiology, Engineering Science and Computing Science, teamed up with dance teacher, Catherine Lee, and several computing science graduate students to create human movement creativity software. The project was funded with the help of a SSHRC grant. They first demonstrated computer methods for the realistic simulation of simple body movements. Then they experimented with user interface design. At first users would specify several of the dancer's locations and shapes in time and space. The computer would fill in the "in-betweens". When choreographers explained that they preferred to think in larger chunks of movement like cartwheels or pirouettes, the interface was changed to give dancers a higher level of abstraction. "Now users can compose *sequences* of complex movements and store them in a menu," says Chris Welman, an MSc student who joined the group in 1987. Sequences can be cut, edited and pasted just like sentences in a word processor.



***Life Forms, the product name of Tom Calvert's dance choreography software originally named COMPOSE, will be marketed by Kinetic Effects of Seattle.***

"From the beginning, COMPOSE was unusual for university research," says Calvert. "We had to make the software more user friendly because our users were dancers not scientists." Unlike most university research that is often inaccessible to the average person, COMPOSE was friendly, intuitive and easy to use. It modelled something everyone knew intimately—the human body.

In the late 80s the group began presenting their work at dance conferences and computer science conventions. When people in Orvieto, Italy read about it, they decided to commission the great New

Reprinted from CSS Update newsletter Vol. 3, No. 3, April 91

*Life Forms research team, left to right, Severin Gaudet, David Yiqun Fu, Richard Campbell, Catherine Lee, Tom Calvert, Sang Mah, Chris Welman, Kim Adamson-Sharpe, Armin Bruderlin. Missing: Marcus Wokowski, Victor Tso, Thecla Schiphorst.*

York choreographer, Merce Cunningham, to computer-choreograph a dance commemorating the 700th anniversary of their town. SFU researchers worked with Cunningham through 1989 and 1990 after installing COMPOSE on a Silicon Graphics workstation in his studio. Stories about Cunningham and COMPOSE have appeared in publications ranging from Dance Magazine to the New York Times.

When hundreds of people began requesting copies of the software, Calvert and his team realized it might have commercial possibilities. "We've had calls from ABC who want to use it in a series on technology and sports," says Welman. MGM has asked about using the software to create a computer sequence for ice skaters in an upcoming movie.

Even before Dean Hovey came along, Calvert had begun talking with SF Univentures about commercializing COMPOSE. In 1990 they decided to form a research society within the lab and to copyright the software. Using grant money from the SFU Precompetitive Incubation Fund, they began work on a Macintosh version for the mass market. Univentures president Alan Cornford acted as a "marriage councillor," helping the group agree on an equitable division of any future profits.

Then Hovey and Larson showed up. Cornford advised Calvert's team throughout their dealings with Hovey. He negotiated the contract on behalf of the team, arranging equity in the company for every student who worked on COMPOSE. Royalties for existing and future products were also secured for the university.

For better marketing clout, it was decided that Kinetic Effects should be located in Seattle. A sister company, Kinetic Effects Research Inc., has been registered in Canada to act as the research arm. "Eighty percent of the work will be done in Canada," says Calvert. The company plans to move into the new Multi-tenant facility in Discovery Park near SFU as soon as construction is completed. "A walk through the trees is the ideal distance between pure research and commercial product development," says Calvert, currently serving a three year term as President of the Science Council of B.C.

Royalties from sales of products based on SFU animation technology will go to the Graphics Laboratory, not to individuals. To begin with, the company plans to market a suite of three products: Life Forms/Mac, Life Forms/SGI (Silicon Graphics Inc.), and a simplified version called Still Life which will be available in both Macintosh and Windows versions. Still Life will create static poses of human body shapes which can be cut and pasted into any presentation, animation or graphics program.

Although the Orvieto project fell through, Cunningham's first computer-choreographed dance performance, "Trackers," was presented at the New York City Centre on March 19, 1991. Critics raved. Yet Hovey and Larson feel that dancers will be only a small part of the market. They expect sports applications to be much bigger. For instance, gymnasts could use the software to plan their routines while football, baseball and basketball teams could teach and analyse plays. The film industry might use Life Forms to storyboard animation or as a tool for planning shots in movies. "You can place your characters on the stage, program their movements complete with body language, then set the camera angle and pretend you're looking right through the lens," says Hovey. But creating interactive characters with idiosyncratic mannerisms is Hovey's vision of the future. Copyrighting and licensing virtual people will be an integral part of the coming multimedia boom.

Both Canadian and American partners feel they have created a marvellous marriage of programming and marketing skills. No wonder Thecla Schiphorst is leaving a tenured teaching job at Douglas College for an uncertain but potentially rewarding future with Kinetic Effects. "I consider myself a lucky human being and I just have a good feeling about this," says Thecla.◊

*"A walk through the trees is the ideal distance between pure research and commercial product development."*

# Superconducting Thin Films

*What became of the wonderful new technologies promised by high-temperature superconductors discovered in the late '80s? At SFU, researchers are testing new microscopic thin-film superconducting loops called SQUIDs (Superconducting QUantum Interference Devices) to make magnetic maps of the human brain.*

One summer day in 1987 CSS member Suso Gygax mixed some copper with the alkaline earth barium and the rare earth yttrium. Like everyone else, he had heard about the Swiss IBM physicists who had discovered that baking these elements together with oxygen formed a new class of high temperature superconductors—materials that conduct electricity with zero resistance. Until then, physicists believed that only a handful of metals like mercury, lead, tin or niobium could become superconductors, and only at temperatures approaching absolute zero. Experiments were routinely conducted in liquid helium at 4° Kelvin or -269°C.

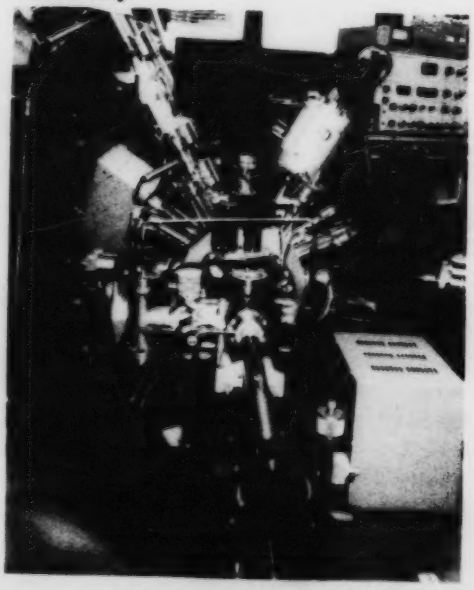
"I got the recipe from the literature and in a day or so I had made the stuff," says Gygax an SFU physics professor. "I've worked in superconductivity at liquid helium temperatures all my life. When I saw the resistance abruptly drop to zero at 89°K it was absolutely incredible. It was so hot!"

The incredibly high temperature of Gygax's experiment was still 184 degrees below zero, cold enough to shatter a banana, but it happened in liquid nitrogen. Unlike helium which requires a room full of equipment for liquefaction, nitrogen is relatively easy to liquefy at 77°K. Liquid nitrogen costs about the same as milk and lasts for a long time because it does not evaporate as quickly as liquid helium.

That summer, the cover of Time magazine predicted an age of superconducting technologies based on the new materials. Since then, progress has been slow but today we are beginning to see microelectronic devices such as thin film high-temperature SQUIDs (Superconducting QUantum Interference Devices), an integral part of a new kind of biomedical scanner that can detect minute magnetic fields emanating from the human body. "The new magnetoencephalographs (MEGs) are much more accurate than EEGs," says CSS member Hal Weinberg, a psychologist who has been working with SQUID powered brain scanners since they were first discovered in the early 80s. A SQUID can detect magnetic fields five billion times weaker than the magnet pinning messages to your fridge. "We are set to do magnetic mapping of the brain," says Weinberg, "and the new high temperature devices make it easier to do the work in human environments. The liquid nitrogen cooled apparatus can be contained in a styrofoam helmet."

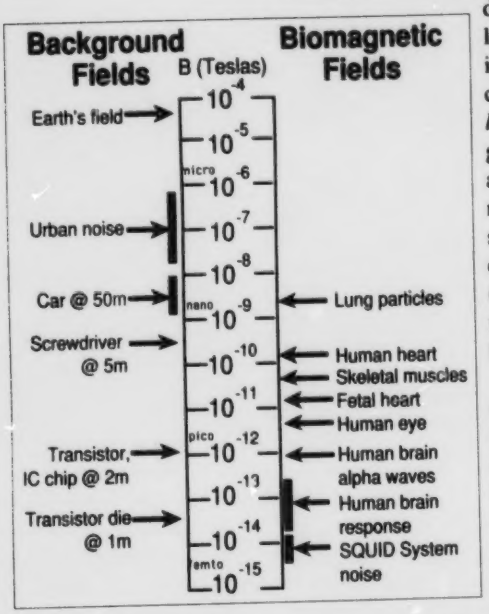
CSS member Brett Heinrich is in charge of the SFU Surface Physics Laboratory. In one project, researchers use a host of high-tech instruments to characterize a high temperature thallium-based superconducting material that is particularly well suited to the manufacture of thin film SQUIDs. The material is made off campus by a local firm. A poisonous thallium compound, $Tl_2Ba_2Ca_2Cu_3O_{12}$, is placed on an electrode in a vacuum chamber while a square centimeter zirconium oxide chip is fixed to a second electrode. Argon and oxygen are introduced into the chamber and 500 volts at 10 MHz radio frequency is applied across the electrodes. Blasted by argon ions, the thallium compound sputters onto the zirconium, coating it with a half-micron thick film in about an hour.

At this point the thin layer is amorphous and non-superconducting. It must be converted into polycrystalline form by sintering at about 850°C with more oxygen. This is the critical step because under the right conditions, the compound will recrystallize into a special lattice structure that orients itself with the atoms of the zirconium substrate. This so called *epitaxial* orientation is thought to be one of the factors that imparts high-temperature superconductivity.



***The Scanning Auger Microprobe is one tool that helps physicists understand high temperature superconductivity. It fires a beam of argon ions to carve away the surface of a material one atomic layer at a time for cross-sectional analysis with a beam of electrons.***

Reprinted from CSS Update newsletter Vol. 3, No. 4, May 91




***The relative strength of common magnetic fields, measured in Teslas.***

A thin film SQUID is made on the chip by forming the thallium material into a half-centimeter diameter superconducting loop with a tiny section that is tightly pinched. This little constriction acts as a *weak link*, a non-superconducting gap in the ring, also known as a *Josephson Junction*, named after the English grad student who predicted its effects in his doctoral thesis ('62) and subsequently shared the 1973 Nobel prize for the discovery.

Physicists are not sure why superconductivity occurs but the popular theory first proposed in 1957 by Bardeen, Cooper and Schrieffer (BCS) suggests that distortions caused by moving electrons within the crystal lattice of a superconducting metal pull other electrons along. At a critical point while temperature is being reduced, resistance suddenly drops to zero. Quantum mechanical effects are thought to cause electron pairing which speeds their movement through the lattice.

Picture a cultivated forest in which large trees have been planted in an orderly grid like the crystal lattice of the superconductor. Then imagine dozens of people on mountain bikes traversing the forest. These are the electrons. When the wind is blowing and tree branches are swaying, the bike riders have to take circuitous paths through the trees, hitting the odd branch and getting slowed down. You can think of superconductivity beginning as the wind slowly dies down. When there's barely a puff of wind, perfectly straight pathways open up between the trees. Suddenly, a mysterious power befalls the bike riders and they become psychically paired—if one goes left, the other goes right even if they are on opposite sides of the forest. Somehow the psychic energy (i.e., quantum mechanical effect) allows them to take off through the trees with absolutely no resistance.

In fact, there is a massive pairing of individual electron angular momenta so that the total momentum of the system adds up to zero. The resulting wave function—a quantum mechanical description of the probability of the electrons' positions in space—becomes the same for all the electrons. In the SQUID loop it's a standing wave. This is the basis for the Josephson effect, whereby superconducting electrons appear to *tunnel* across the weak link in the loop. Because the quantum state of the electrons is a standing wave all around the ring, there is a strong probability that they will make it over the non-superconducting gap. It's as though the psychic pairing of the bike riders helps them cross a narrow gully in the woods.

Superconducting rings normally shun external magnetic fields, but when even a tiny magnetic field is applied to a ring with a weak link, quantum effects cause the superconductivity to vanish briefly and a potential difference can be measured. This is how SQUIDs detect up to 10,000 times less magnetism than the next best magnetometer.

The old BCS theory for superconductivity breaks down at high temperatures. Lab director Brett Heinrich says, "Although we know what parameters affect high temperature superconductivity, we still have no acceptable theory." Physicists believe the theory has to do with "holes"—places where electrons aren't—rather than actual electrons in the crystal lattice. Holes can also be viewed as current conducting entities. All the new superconducting materials are ceramic oxides with plenty of holes. Gygax's favourite theory: there are strong lattice vibrations which are quantized like light and they couple with "a sea of holes." Only time will tell if he's right or wrong.

Gygax is collaborating with CSS Engineering Science members like Ash Parameswaran and Jamal Deen to make high temperature superconducting thin films on silicon instead of zirconia. Besides being much cheaper, silicon substrates promise a world of marvellous superconducting devices.◊

## Tools For Materials Research at SFU

- **Electron Dispersive X-ray (EDX).** This machine bombards a sample with an electron beam, detecting the X-rays radiated by various elements in the substance to get the relative proportion and identity of its constituent atoms.
- **X-ray Diffractometer.** From the angle of refraction of X-rays passing through a sample scientists can infer its crystalline structure. They can also obtain information about the quality of the material—whether it contains impurities.
- **Raman Spectroscope.** This device records scattered light from a laser shining on the sample, giving information about the surface atoms only. Oxygen atom vibrations measured by the Raman spectroscope can predict whether or not a compound will be a superconductor.
- **Scanning Auger Microprobe (SAM).** Shoots a beam of argon ions that can dig a 1.5 mm hole in the surface of a sample destroying material a couple of atomic layers at a time. A beam of electrons is then fired into the hole. Secondary electrons that come out yield compositional details of each atomic layer as the argon beam digs down. This gives scientists a cross-sectional depth profile and tests for homogeneity of the sample.
- **X-ray Photo-electron Spectroscope (XPS).** Surface scientists use this to radiate a material with high energy light quanta that blast away electrons revealing the electronic structure of the material. Differences between superconductors and non-superconductors hint at theories for high-temperature superconductivity.

# The Leap Into Cyberspace

*"Cyberpunk" is a genre of science fiction in which the world's computers are connected in a vast matrix called Cyberspace. Keyboard cowboys jack-in brain-first to explore terrabytes of information and haunting virtual constructs. But CSS members do not have to wait for the future or read about it in science fiction novels. Our Research Science Computer Network already connects most CSS scientists together. It also taps into the Internet—the largest computer network in the world.*

A member on sabbatical, Joe Peters, sent us electronic mail describing how he edits papers in France: "I pull the file over the Internet from SFU using ftp, edit it here, send it back, run it through psroff at SFU [to create a laser printable version], pull the resulting .ps file back here, and print it on a local laser printer. How's that for an example of distributed computing?"

The CSS network belongs to Internet, part of a global matrix of networks including ARPANET, BITNET, USENET, CSNet, NSFnet, and countless others. Such huge networks seem to trivialize the physical location of the worker. The only important factor is the location of the nearest laser printer. Everything else is no farther away than five or ten keystrokes.

CSS member, Bill Richards, says, "I was in Helsinki, sitting in this guy's office at the University. He had a computer on his desk. I asked him if it was connected to a campus machine. He said it was. A UNIX system. So I asked him to sign on. Then I typed `telnet cc.sfu.ca` and waited about five seconds. It said `connected` and I was in! I was amazed. It's a world network."

Vancouver science fiction writer, William Gibson, calls the matrix *cyberspace* in his futuristic novels, but it's almost here now. In the early 1970's the world network sprung from ARPANET, the American military network of advanced research computers, mostly UNIX machines on university campuses. In late 1979, two Duke University grad students thought of using UUCP (UNIX to UNIX CoPy) for hooking computers together to exchange information in the UNIX community. Thus USENET, the UNIX news sharing system, was born. There were only three connected machines in 1979 but by 1981 the number had grown to 100. The software continued to be improved to meet the demand of an ever increasing number of sites. By 1986 enhanced batching, data compression, TCP/IP (Transfer Control Protocol/Internet Protocol) and other features were added.

At the same time that ARPANET and USENET were growing in the UNIX community, BITNET was evolving on IBM machines. BITNET uses a different set of protocols based on IBM's VM operating system. Eventually, various networks began talking to each other through gateway machines—computers that could translate communication protocols between systems. In the last couple of years most of the world's research computer networks have been connected like this to form a global network.

August 1990 USENET statistics—posted monthly in the news area called news.lists—estimate the number of network sites to be 29,000 with 5 million potential users. Of these, about a million read and generate 12 megabytes of news every day. In addition to network news, which anyone can read with the UNIX commands `readnews`, `vnews` or `rn`, other network activity is generated by `email` (electronic mail), `ftp` (see next page), and `telnet`. As Bill Richards found out, telnet lets you log in to a remote computer on the other side of the world.

But you don't need to be that far away to make use of the network. A more local network called BC Net connects the major universities, government offices and corporate sites in the province. SFU researchers can use the net to contact colleagues or log on to computers at these sites. They can do library searches at SFU and even UBC (`telnet library.ubc.ca`) You need a UBC library card number but SFU faculty and grad students can get them free over the phone. The Vancouver Public Library will be on BC Net in December 1990. BC Net is also our gateway to the global networks.

Art Liestman, Director of the School of Computing Science, studies theories of networking and is delighted by the Internet, but he cautions: "Although we have this great network we don't use its potential. We don't run distributed applications that exploit the fact that we *have* this network. We do email and ftp over long distances but fundamentally we are just users. What do we really contribute to the global network community?"

But CSS member Glenn Chapman *is* contributing something. One of our newest members, Glenn is

an ASI Fellow and Professor of Engineering Science. He has started a computerized newsletter called "The Micromachining Digest." "Micromachining and sensors is a growing field with researchers scattered throughout the world," says Glenn. "To help promote communications between interested parties, our Micromachining/Sensors group has created this newsletter for distribution on the Internet." Glenn will be the moderator of the new digest. If you want to receive it, email him at glennc@cs.sfu.ca.

So much information clutters the networks that digests like Glenn's have become indispensable to regular net users. Digests are different from ordinary newsgroups because you don't receive anything unless you specifically request to be on the mailing list. Such publicly accessible mailing lists can be joined only by emailing a request to the moderator. A list of all such mailing list groups and their moderators is regularly posted to the USENET news group called news.lists. (To read this or any other newsgroup try the UNIX command `readnews <groupname>` where <groupname> is the name of the newsgroup you want.) It currently lists about a hundred topics ranging from origami to outer space.

There are also hundreds of moderated and unmoderated groups that appear on USENET. Some are useful to your research (conference announcements) while others are of questionable value (alt.sex.bondage, alt.tv.twinpeaks). Brian Funt says, "It seems that a lot of people waste most of their day reading the net news." And he's right, but it's probably better to read the net news than to watch TV in the evening. There's no advertising and it's more interactive: you can ask for more information, add your own expertise or enter into debates.

How much does it all cost us? According to Ian Williams, Director of the Computing Centre, SFU pays $30,000/year for our BC Net connection which includes the gateway to the Internet.◊

## "How Did You Get It?" "I ftp'd It!"

*John Jones*

"Connecting to a remote site for ftp [file transfer protocol] is a slightly uncanny feeling—the responses to your commands come back sometimes after a pause of seconds, and you're aware that the movement of your fingers on the keyboard is causing electric currents to flow inside a machine in Melbourne or Helsinki." That's how CSS member John Jones describes the UNIX command, ftp.

You use ftp to transfer files between two computers connected via the Internet. You can access your own files from a remote site, or you can browse huge archives of information available to anonymous users on hundreds of systems around the world. They contain different things—useful bits of C code, shareware programs for your Mac or PC, digitized recordings of birdsong, bit-mapped pictures of Neptune sent back by Voyager, and dormant viruses. Jones likens it to a "Dungeons and Dragons" type of fantasy game in which you navigate an unmapped labyrinth of caves, discovering treasures, magic scrolls and homicidal dwarves.

If you have never done it, try downloading a game for your PC from `wsmr-simtel20.army.mil`. That's right, White Sands Missile Range, one of the world's biggest archives of public domain PC software. Or you might want to get something like a Kookaburra from the big archive of Macintosh software at Stanford:

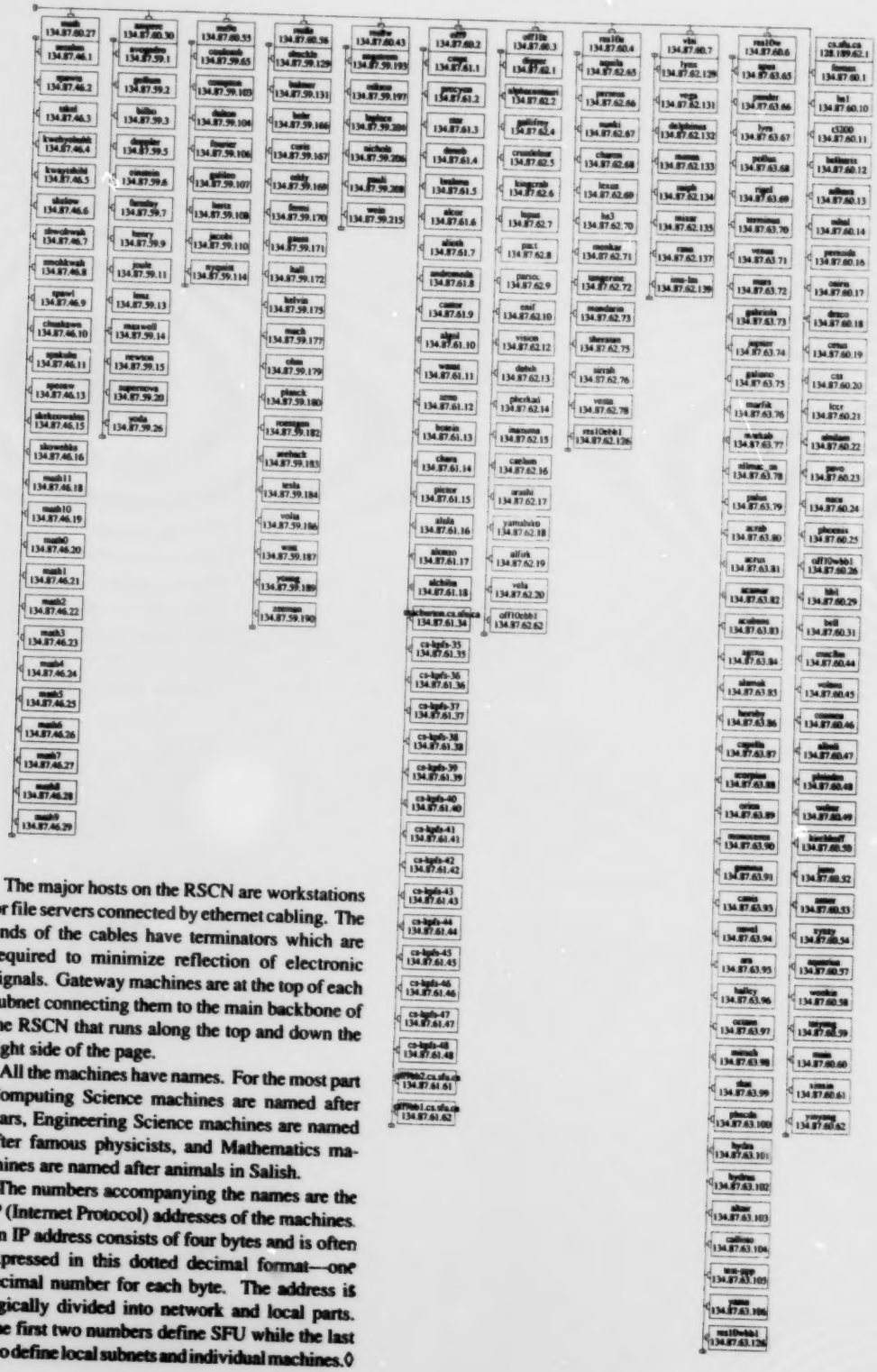
```
5: css% ftp sumex-aim.stanford.edu
Connected to 36.44.0.6.
220 sumex-aim FTP server (SunOS 4.0/3) ready.
Name (36.44.0.6:shell): anonymous
331 Guest login ok, send ident as password.
Password:
230 Guest login ok, access restrictions apply.
ftp> cd info-mac
250 CWD command successful.
ftp> get ./sound/aussie-bird-songs.hqx
200 PORT command successful.
150 ASCII data connection for aussie-bird-songs.hqx
(134.87.60.20,1830) (170662 bytes).
226 ASCII Transfer complete.
173293 bytes received in 62 seconds (2.7 Kbytes/s)
ftp> bye
221 Goodbye.
```

When the remote site asks for your name, type `anonymous`. A password is optional but it's good manners to enter your email address. Commands like `ls` (list files) and `cd` (change directory) act just as if you were on your own machine. For other commands type help. You can ftp pilot.njin.net to get a list of all known anonymous ftp sites.

But please use caution. Anonymous ftp is a privilege, not a right. Remote sites have made their systems available out of the goodness of their hearts. Please respect their wishes and restrict your ftp'ing to non-prime hours (1900 - 0600 hours local time for the site). This is especially true for sites not in your country. Please keep that in mind when you are ftp'ing. None of us want to see sites start to close down because a few people are being inconsiderate.◊

# CSS Research Network Map

*The CSS supports a network of over 400 computers with 500 users spanning 14 departments at SFU.*



The major hosts on the RSCN are workstations or file servers connected by ethernet cabling. The ends of the cables have terminators which are required to minimize reflection of electronic signals. Gateway machines are at the top of each subnet connecting them to the main backbone of the RSCN that runs along the top and down the right side of the page.

All the machines have names. For the most part Computing Science machines are named after stars, Engineering Science machines are named after famous physicists, and Mathematics machines are named after animals in Salish.

The numbers accompanying the names are the IP (Internet Protocol) addresses of the machines. An IP address consists of four bytes and is often expressed in this dotted decimal format—one decimal number for each byte. The address is logically divided into network and local parts. The first two numbers define SFU while the last two define local subnets and individual machines.◊

# Additive Spanners for Hypercubes

Arthur L. Liestman and Thomas C. Shermer

*A t-spanner of a network is a subnetwork in which every two nodes that were connected by an edge in the original network are connected by a path of at most t edges in the subnetwork. This guarantees that if nodes u and v are at distance d(u,v) in the original network, they are at distance no more than t · d(u,v) in the t-spanner. We introduce a more general definition of spanners. A special case of this more general definition is the additive t-spanner: a subnetwork in which every two nodes u and v that were separated by distance d(u,v) in the original network are at distance no more than t + d(u,v) in the subnetwork. We construct low-degree additive t-spanners for hypercubes.*

## 1. Introduction and Definitions

There are several popular topologies used for constructing parallel computers. Some of these structures, such as the hypercube, have relatively high degree at each vertex. Our goal is to determine substructures of such topologies with fewer edges or smaller maximum degree. We require also that these substructures, called *spanners*, have the property that the distance between two vertices in the substructure is not significantly larger than the corresponding distance in the original structure.

Spanners were introduced by Peleg and Ullman[1] who used these structures in order to efficiently simulate synchronous networks on asynchronous networks. Another motivation for studying spanners is their possible use as network topologies. A spanner can be used as a substitute for a desired network, often giving a much sparser network with a similar structure and slightly larger communication costs. As defined by Peleg and Ullman, spanners can provide an efficient network topology if communications are localized, each processor communicating only with its neighbors. However, a more general formulation is required to express spanner efficiency if messages are to be passed between distant processors. In this paper, we provide such a formulation.

A network is represented by a connected simple graph $G = (V, E)$. We use the notation $d_G(u,v)$ to denote the distance between vertices $u$ and $v$ in graph $G$. The maximum degree of a graph is denoted $\Delta_G$ and the average degree is denoted $\delta_G$. The subscript $G$ may be omitted if it is clear from context.

According to Peleg and Ullman, a spanning subgraph $S = (V, E')$ of $G$ is a $t$-spanner if for any edge $ab$ of $G$ there is a path from $a$ to $b$ in $S$ with $t$ or fewer edges. Alternatively, a $t$-spanner $S$ could be defined to be a spanning subgraph of $G$ such that for any pair of vertices $u$ and $v$, $d_S(u,v) \le t \cdot d_G(u,v)$.

We begin by introducing a more general definition of graph spanner: A spanning subgraph $S = (V, E')$ of a connected simple graph $G = (V, E)$ is a *$f(x)$-spanner* if for any pair of nodes $u$ and $v$, $d_S(u,v) \le f(d_G(u,v))$. In our terminology, what Peleg and Ullman would call a $t$-spanner is called a $tx$-spanner. For the remainder of this paper, we will be interested in $(t+x)$-spanners. We sometimes refer to $tx$-spanners as multiplicative spanners and $(t+x)$-spanners as additive spanners. The word spanner is used to denote any $f(x)$-spanner.

Peleg and Schäffer[2] investigated the existence and constructability of sparse multiplicative spanners for various classes of graphs. They showed that to determine for a given graph $G$ and integer $m \ge 1$, whether $G$ has a $2x$-spanner with $m$ or fewer edges is NP-complete. Cai[3] showed that, for any integer $t \ge 2$, to determine for a given graph $G$ and integer $m \ge 1$ whether $G$ has a $tx$-spanner with $m$ or fewer edges is NP-complete. Richards and Liestman[4] began an investigation of degree-constrained multiplicative spanners by studying these substructures in pyramids. Liestman and Shermer[5] continued this study, considering spanners of multidimensional grids and hypercubes.

In a companion paper[6], we show that, for an arbitrary integer $t > 0$, to determine for a given graph $G$ and integer $m \ge 1$ whether $G$ has an additive $t$-spanner with no more than $m$ edges is NP-complete, and give constructions for low-degree additive $t$-spanners for other graphs including pyramids and multidimensional grids.

In Section 2 we produce a simple $(2+x)$-spanner of the $d$-cube. In Section 3 we describe a general method to construct additive spanners for hypercubes which we use in Section 4 to produce such spanners.

## 2. A Simple Additive Spanner for Hypercubes

We now show that our multiplicative hypercube spanner construction from a previous paper[5] also gives an additive spanner. In the proof below, we use the fact that each edge of a hypercube connects two vertices whose labels differ in one bit. Thus, traveling along an edge corresponds to flipping a bit in the vertex label or moving in one dimension.

**Theorem 1** *For the d-dimensional hypercube, there exists a $(2+x)$-spanner with $\Delta = \lceil (d+1)/2 \rceil$ and $\delta = (d+1)/2$.*

**Proof.** To construct a $(2+x)$-spanner of the $d$-cube, include only the following edges. Connect each vertex $(0,u_2,\ldots,u_i,\ldots,u_d)$ to vertex $(0, u_2,\ldots,(u_i+1) \bmod 2,\ldots,u_d)$ for all even $i$. Connect each vertex $(1,u_2,\ldots,u_i,\ldots,u_d)$ to vertex $(0, u_2,\ldots,(u_i+1) \bmod 2,\ldots,u_d)$ for all odd $i > 1$. In addition, each vertex

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$(0,u_2,\ldots,u_d)$ is connected to $(1,u_2,\ldots,u_d)$. Vertices with $u_1 = 0$ have degree $\lceil d/2 \rceil$ while vertices with $u_1 = 1$ have degree $\lceil (d+1)/2 \rceil$, thus $\Delta = \lceil (d+1)/2 \rceil$ and $\delta = (d+1)/2$.

To describe a short path between $u$ and $v$ in the spanner, we first consider the case in which $u_1 = 0$ and assume that $u$ and $v$ differ in $k$ bits. We refer to $u_i$ as an odd bit if $i$ is odd and as an even bit, otherwise. A path between $u$ and $v$ in the spanner consists of a sequence of bit flips, $k$ of which correspond to the $k$ bits in which the labels differ. First, flip all of the even bits in which $u$ and $v$ differ (in any order). This is possible because $u_1$ remains 0 and all such vertices are connected to their neighbors in the even dimensions. Change the first bit to 1. Then, flip all of the odd bits (except bit 1) in which $u$ and $v$ differ (in any order). If $v_1 = 0$, change the first bit back to 0. Clearly, the number of bits flipped is no more than $k+2$. The case of $u_1 = 1$ is essentially the same except that the odd bits are flipped first.□

The diameter of this spanner is $d+1$, one more than the diameter of the $d$-cube. In the $d$-cube, any pair of vertices which realizes the diameter must differ in the first bit. Therefore, the final change of the first bit is not necessary. The distance between any other pair of vertices is at most $d$-1 in the $d$-cube and, therefore, at most $d+1$ in the spanner. In fact, there are pairs of vertices at distance $d$-1 in the $d$-cube which are at distance $d+1$ in the spanner.

This spanner has practical applications. Within given degree constraints we can build a spanner of nearly double the dimension of the achievable hypercube. For example, suppose that we want to build a hypercube and are limited to seven connections per processor, due to layout constraints. Building the full hypercube topology would allow us to construct a 7-cube containing 128 processors. However, with the same number of connections per processor, we can build a $(2+x)$-spanner of the 13-cube containing 8192 processors. In this spanner, routing a message is simple (following the path described in the proof above), distance (communication time) between any 2 processors is at most 2 more than the distance in the full 13-cube, and the diameter (maximum communication time) is at most 1 more than the diameter of the full 13-cube. Alternatively, for a fixed dimension, the $(2+x)$-spanner contains roughly half the number of edges of the full hypercube.

## 3. General Method to Construct Additive Spanners for Hypercubes

We begin with some necessary definitions. A *Hamiltonian walk* is a walk from vertex $a$ to vertex $b$ in $G$ which includes all of the vertices of $G$. Let the *Hamiltonian distance*, denoted $hd_G(a,b)$, be the number of edges in a minimum length Hamiltonian walk from $a$ to $b$ in $G$. We define the *Hamiltonian diameter*, denoted $HD(G)$, to be $\max_{a,b}\{hd_G(a,b)\}$ where $a$ and $b$ are (not necessarily distinct) vertices of $G$. Thus, the Hamiltonian diameter of $G$ is the largest Hamiltonian distance between any pair of vertices in $G$. It is well-known that the Hamiltonian diameter of the $d$-dimensional hypercube is $2^d$.

In the spanner described above, the first dimension is treated differently than the other dimensions. In particular, all of the edges in dimension 1 are present. There is an edge (1-cube) between every pair of vertices $(0,u_2,\ldots,u_d)$ and $(1,u_2,\ldots,u_d)$, that is, there is a 1-cube between every set of 2 vertices which have the same last $d$-1 co-ordinates.

We can generalize this by including all of the edges (of the $j$-cube) of the first $j$ dimensions in the spanner. Then there is a $j$-cube connecting every set of $2^j$ vertices with the same last $d$-$j$ co-ordinates. In addition to these edges, we connect each vertex $u = (u_1,\ldots,u_i,\ldots,u_d)$ to vertex $v = (u_1,\ldots,(u_i+1) \bmod 2,\ldots,u_d)$ for all $i > j$ and $i \equiv k \bmod 2^j$ where $k$ is the integer corresponding to the binary string $u_1u_2\ldots u_j$.

To find a path between vertices $u$ and $v$ of the generalized spanner, we first find a Hamiltonian walk $W$ from $(u_1,\ldots,u_j,\ldots,u_j)$ to $(v_1,\ldots,v_j,\ldots,v_j)$ in the $j$-cube. If $u$ and $v$ differ in any bit position $k > j$, then this bit can be flipped at the appropriate point on this walk, i.e. at the vertex of the $j$-cube with label equivalent to $k \pmod{2^j}$.

We can modify this construction in the following manner. Rather than connecting each set of $2^j$ vertices having the same last $d$-$j$ co-ordinates with the edges of a $j$-cube, we can obtain a spanner with fewer edges by connecting them with the edges of a *spanner* of the $j$-cube. Although any spanner of the $j$-cube can be used, spanners with smaller Hamiltonian diameters yield better spanners of the $d$-cube.

**Theorem 2** *Given a spanner $S$ of the $j$-cube with maximum degree $\Delta_S$ and average degree $\delta_S$, we can construct a $(HD(S) + x)$-spanner $T$ of the $d$-cube $G$, $d \geq j$, with maximum degree $\Delta_T$ such that $\Delta_S + \lceil (d-j)/2^j \rceil - 1 \leq \Delta_T \leq \Delta_S + \lceil (d-j)/2^j \rceil$ and average degree $\delta_T = \delta_S + (d-j)/2^j$.*

**Proof.** To construct the spanner $T$, include only the edges of $S$ in the first $j$ dimensions to connect each set of $2^j$ vertices which have the same last $d$-$j$ co-ordinates. In addition to these edges, we connect each vertex $u = (u_1,\ldots,u_i,\ldots,u_d)$ to vertex $v = (u_1,\ldots,(u_i+1) \bmod 2,\ldots,u_d)$ for all $i > j$ and $i \equiv k \bmod 2^j$ where $k$ is the integer corresponding to the binary string $u_1u_2\ldots u_j$. Thus, depending on the string $u_1u_2\ldots u_j$, the vertex $u$ will have $\lceil (d-j)/2^j \rceil$ or $\lceil (d-j)/2^j \rceil - 1$ incident edges in the last $d$-$j$ dimensions. This means that $T$ has maximum degree $\Delta_T$ such that $\Delta_S + \lceil (d-j)/2^j \rceil - 1 \leq \Delta_T \leq \Delta_S + \lceil (d-j)/2^j \rceil$. Also, $T$ has average degree $\delta_S + (d-j)/2^j$.

To prove that the resulting structure is a $(HD(S) + x)$-spanner of the $d$-cube, it remains to show that for any pair of vertices $u$ and $v$ separated by distance $d(u,v)$ in the $d$-cube, $d_T(u,v) \leq d(u,v) + HD(S)$.

Consider vertices $u = (u_1,\ldots,u_d)$ and $v = (v_1,\ldots,v_d)$ in the $d$-cube whose labels differ in $k$ bits. Then $d(u,v) = k$ and any shortest path from $u$ to $v$ corresponds to flipping the $k$ bits in which the labels differ in some order. A path between $u$ and $v$ in the spanner $T$ can be constructed as follows. Let $u'$ and $v'$ denote the first $j$ bits of the labels $u$ and $v$, respectively. To construct a path from $u$ to $v$, begin with a shortest Hamiltonian walk $W$ from $u'$ to $v'$ in the $j$-cube. If no other bits need

to be flipped, that is, if $u$ and $v$ only differ in the first $j$ bits, then the corresponding walk between $u$ and $v$ is contained in $T$ and $d_T(u,v) \le hd_S(u',v') \le HD(S)$. In general, however, the bits in which $u$ and $v$ differ will be contained in both parts of the labels. By our construction, each vertex $z = (z_1,\ldots,z_i,\ldots,z_d)$ in the $d$-cube is connected to vertex $(z_1,\ldots,(z_i+1) \bmod 2,\ldots,z_d)$ for all $i > j$ and $i \equiv k \bmod 2^j$ where $k$ is the integer corresponding to the binary string $z_1z_2\ldots z_j$. Thus, when we arrive at some vertex whose first $j$ bits are $z_1,z_2,\ldots,z_j$, we can flip the necessary bits in positions $i \equiv k \bmod 2^j$ where $k$ is the integer corresponding to the binary string $z_1z_2\ldots z_j$. Since the Hamiltonian walk $W$ passes through every vertex of the $j$-cube, we can form a path from $u$ to $v$ by augmenting the path $W$ with additional steps in the other $d$-$j$ dimensions. Since we need only flip those bits in the last $d$-$j$ positions in which $u$ and $v$ differ, the resulting walk $W'$ is of length no more than $k + hd_S(u',v') = d_G(u,v) + hd_S(u',v') \le d_G(u,v) + HD(S)$.□

## 4. Additive Spanners for Hypercubes

We can obtain an additive spanner for the $d$-cube using the general method described in the previous section by including all of the edges of a $j$-cube in the first $j$ dimensions.

**Theorem 3** *For any $j$ such that $1 \le j \le d$, there exists a $(2^j+x)$-spanner for the $d$-dimensional hypercube with $\Delta = \lceil (d-j)/2^j \rceil + j$ and $\delta = (d-j)/2^j + j$.*

**Proof.** The existence and construction of the spanner follow from Theorem 2 and the Hamiltonian diameter of the $j$-cube. Note that $\Delta = \lceil (d-j)/2^j \rceil + j$ since all vertices are connected to all of their neighbors in the first $j$ dimensions.□

The special case of this theorem for $j = 1$ is the $(2+x)$-spanner described in Section 2. In general, this theorem provides a tradeoff between the additive communication delay and the degree at each vertex. Small $j$ gives a small communication delay while large $j$ gives smaller degree. For example, if $d$ is large, increasing the value of $j$ by one roughly halves the degree at each vertex while at most doubling the extra distance between any pair of vertices.

We can obtain an additive spanner of the $d$-cube with fewer edges using the edges of a $j$-cube $(2+x)$-*spanner* (as described in Section 2) in the first $j$ dimensions. The following lemmas are required.

**Lemma 1** *Let $e = uv$ be any edge in the $(2+x)$-spanner $S$ of the $d$-dimensional hypercube, for $d \ge 3$. $S$ has a Hamiltonian path between $u$ and $v$.*

**Proof.** We prove this by induction. For $d = 3$, $S$ is a circuit, thus the lemma holds. We assume, inductively, that the result is true for $d$.

Consider two vertices $u$ and $v$ of a $(d+1)$-cube. The vertices of the spanner $S$ can be partitioned into two subsets, $V_0$ and $V_1$, according to the value of the last bit position. We note that the subgraphs $S_0$ and $S_1$ induced by $V_0$ and $V_1$, respectively, are $(2+x)$-spanners of the corresponding $d$-cubes.

Consider the case when $u$ and $v$ are in the same subset; without loss of generality, let them be in $V_0$. By the inductive hypothesis, there exists a Hamiltonian path $P$ in $S_0$ between $u$ and $v$. This path $P$ has an edge $ab$ in dimension $d$-1, that is, $a = (u_1,\ldots,u_{d-2},0,u_d,0)$ and $b = (u_1,\ldots,u_{d-2},1,u_d,0)$. Let $a' = (u_1,\ldots,u_{d-2},0,u_d,1)$ and $b' = (u_1,\ldots,u_{d-2},1,u_d,1)$. Again, by the inductive hypothesis, there exists a Hamiltonian path $P'$ in $S_1$ between $a'$ and $b'$. Note that, there is an edge $a'b'$ in $S_1$ since there is an edge $ab$ in $S_0$. We replace $ab$ in $P$ by the edge $aa'$ followed by the path $P'$ followed by the edge $b'b$ to form a Hamiltonian path from $u$ to $v$. (Note that $aa'$ and $b'b$ are edges in $S$ since $u_1 \equiv d+1 \equiv d-1 \pmod 2$.)

Consider the case when $u$ and $v$ are in different $d$-cubes; without loss of generality, let $u$ be in $V_0$ and $v$ be in $V_1$. Let $u = (u_1,\ldots,u_{d-2},u_{d-1},u_d,0)$ and $v = (u_1,\ldots,u_{d-2},u_{d-1},u_d,1)$. Let $a = (u_1,\ldots,u_{d-2},(u_{d-1} + 1) \bmod 2,u_d,0)$ and $b = (u_1,\ldots,u_{d-2},(u_{d-1} + 1) \bmod 2,u_d,1)$. Note that the edges $ua$, $ab$, and $bv$ are all in $S$ since $u_1 \not\equiv d+1 \not\equiv d-1 \pmod 2$. By induction, we have a Hamiltonian path $P_0$ in $S_0$ from $u$ to $a$ and a Hamiltonian path $P_1$ in $S_1$ from $b$ to $v$. The path from $u$ to $v$ formed by $P_0$, followed by the edge $ab$, followed by $P_1$ is a Hamiltonian path in $S$.□

**Lemma 2** *The $(2+x)$-spanner of the $d$-dimensional hypercube has Hamiltonian diameter $2^d + 2$.*

**Proof.** The proof is by induction on $d$ and is easily observed to be true for $d = 1$, 2 or 3. We assume, inductively, that the result is true for $d$.

Consider two vertices $u$ and $v$ of the $(2+x)$-spanner $S$ of a $(d+1)$-cube. The vertices of the spanner $S$ can be partitioned into two subsets, $V_0$ and $V_1$, according to the value of the last bit position. We note that the subgraphs $S_0$ and $S_1$ induced by $V_0$ and $V_1$, respectively, are $(2+x)$-spanners of the corresponding $d$-cubes.

Consider the case when $u$ and $v$ are in the same subset; without loss of generality, let them be in $V_0$. By the inductive hypothesis, there exists a Hamiltonian walk $W$ in $S_0$ between $u$ and $v$ of length no more than $2^d + 2$. This walk $W$ has an edge $ab$ in dimension $d$-1, that is, $a = (u_1,\ldots,u_{d-2},0,u_d,0)$ and $b = (u_1,\ldots,u_{d-2},1,u_d,0)$. Let $a' = (u_1,\ldots,u_{d-2},0,u_d,1)$ and $b' = (u_1,\ldots,u_{d-2},1,u_d,1)$. Again, by Lemma 1, there exists a Hamiltonian path $P$ in $S_1$ between $a'$ and $b'$. Note that, there is an edge $a'b'$ in $S_1$ since there is an edge $ab$ in $S_0$. We replace $ab$ in $W$ by the edge $aa'$ followed by the path $P$ followed by the edge $b'b$ to form a Hamiltonian walk from $u$ to $v$. (Note that $aa'$ and $b'b$ are edges in $S$ since $u_1 \equiv d+1 \equiv d-1 \pmod 2$.) The number of edges in the walk $W$ is at most $(2^d + 2 - 1) + 1 + (2^d - 1) + 1 = 2^{d+1} + 2$.

Consider the case when $u$ and $v$ are in different $d$-cubes; without loss of generality, let $u$ be in $V_0$ and $v$ be in $V_1$. Let $u = (u_1,\ldots,u_{d-2},u_{d-1},u_d,0)$. Let $a = (u_1,\ldots,u_{d-2},(u_{d-1} + 1) \bmod 2,u_d,0)$ if $u_1 \equiv (d-1) \pmod 2$ and $a = ((u_1 + 1) \bmod 2, u_2, \ldots, u_d, 0)$ otherwise. Note that by our choice of $a$, there is some vertex $b$ in $V_1$ adjacent to $a$ in $S$. In either case, there is a Hamiltonian path $P$ from $u$ to $a$ in $S_0$ by Lemma 1. By the inductive hypothesis, there is a Hamiltonian walk $W$ from $b$ to $v$ in $S_1$ of length no more than $2^d + 2$. The walk from $u$ to $v$ formed by $P$, followed by the edge $ab$, followed by $W$ is a Hamiltonian walk in $S$. The number of edges

in the walk $W$ is at most $(2^d - 1) + 1 + (2^d + 2) = 2^{d+1} + 2$.□

The previous lemma and Theorem 2 give us the following result.

**Theorem 4** *For any $j$ such that $1 \le j \le d$, there exists a $(2^j+2+x)$-spanner for the $d$-dimensional hypercube with $\lceil (d-j)/2^j \rceil + \lceil (j+1)/2 \rceil - 1 \le \Delta \le \lceil (d-j)/2^j \rceil + \lceil (j+1)/2 \rceil$ and $\delta = (d-j)/2^j + (j+1)/2$.*

As with Theorem 3, the value of $j$ in this theorem controls a tradeoff between the additive communication delay and the degree at each vertex.

Suppose that we wish to construct a hypercube $(t+x)$-spanner of maximum dimension subject to constraints on the maximum degree and on the communication time. Either of the two constructions from this section may yield a larger structure. For example, with constraints $\Delta \le 10$ and $t \le 20$, Theorem 3 (with $j$=4) yields a spanner of a 100-cube, while Theorem 4 (with $j$=4) yields a spanner of a 116-cube. On the other hand, if the constraints are $\Delta \le 10$ and $t \le 4$, Theorem 3 (with $j$=2) yields a spanner of a 34-cube, while Theorem 4 (with $j$=1) yields a spanner of a 19-cube.

Note that for any fixed $j$, the spanner obtained from Theorem 4 has $\Delta$ about j/2 smaller than the corresponding spanner obtained from Theorem 3, while its additive communication delay is only two greater. Thus, the construction of Theorem 4 will generally be preferable when $j$ is large and a small $\Delta$ is required. However, message routing is somewhat more complicated in the spanners described by Theorem 4.

## 5. Conclusion

Graph spanners were originally studied for their use in synchronization of distributed algorithms. In this paper, we provide a more general definition which is more appropriate in the context of interconnection networks. We concentrate on additive spanners, which allow a small additive constant increase in communication time. The main results of the paper show how to construct additive spanners for hypercubes. We describe a general construction technique and show how to use it to construct a $(2^j+x)$-spanner and a $(2^j+2+x)$-spanner for the $d$-cube (where $j \le d$).

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# Sophisticated Natural Language Interfaces, Possibility or Chimaera?

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*We investigate problems of constructing a sophisticated natural language interface to a database. Such systems must access knowledge in a knowledge base, rather than simply data in a database to be truly sophisticated and useful to decision makers. For example, if a system responded to the question "Is model R2D2 for sale?" with "Yes, in limited quantities and by special order.", more appropriate information is available to the user upon which to base decisions. We illustrate a number of concerns which will have to be taken into account using numerous examples and show how important it is to incorporate knowledge of the domain, of the user, and of discourse structure into the system. We describe SystemX, the natural language interface built in the Natural Language Laboratory.*

## Introduction

Contemporary methods for automated natural language processing depend, to a large extent, on the use to which each application of the processing is to be put. Consider the following excerpt from Erle Stanley Gardner's "The Case of the Demure Defendant":

"Cross-examine," Hamilton Burger snapped at Perry Mason.

Mason said, "Mr. Dayton, when you described your occupation you gave it as that of a police expert technician. Is that correct?"

"yes sir."

"What is an expert technician?"

"Well, I have studied extensively on certain fields of science that are frequently called upon in the science of criminology."

"That is what you meant by an expert technician?"

"Yes sir."

"Now what is a police expert technician?"

"Well that means that ... well, it all means the same thing."

"What means the same thing?"

"An expert technician."

"An expert technician is the same as a police expert technician?"

"Well I am in the employ of the police department."

"Oh the police employ you as an expert witness, do they?"

"Yes sir, ... I mean no, sir. I am an expert investigator, not an expert witness."

"You are testifying now as an expert witness are you not?"

"Yes sir."

"Then what did you mean by saying you were an expert technician but not an expert witness?"

"I am employed as a technician but not as a witness."

"You draw a monthly salary?"

"Yes."

"And you are being paid for your time while you are on the stand as an expert witness?"

"Well, I'm paid for being a technician"

"Then you won't accept any pay for being a witness?"

"I can't divide my salary."

"So you are being paid?"

"Of course - as part of my employment."

"And are you now employed by the police?"

"Yes."

"And are you an expert witness?"

"Yes."

"Then you are now being employed as an expert witness."

"I guess so. Have it your own way."

"When you described yourself as a police experttechnician that means your testimony is always calledby the police. Isn't that so?"

"No, sir."

"Who else calls you?"

"Well, I ... I could be called by either party."

"How many times have you been on the witness stand?"

"Oh, I don't know. I couldn't begin to tell you."

"Dozens of times?"

"Yes."

"Hundreds of times?"

"Probably."

"Have you ever been called by the defense as a defense witness?"

"I have not been directly subpoenaed by the defense. No, sir."

"So that you have always testified for the police, for the prosecution?"

"Yes, sir. That's my business."

"That was what I was trying to bring out," Mason said.

Imagine, if you will, the processing required to emulate the part of Mr. Dayton. Mr. Dayton needs to understand the subtleties of noun phrases such as "police expert technician", in order to answer Mr.

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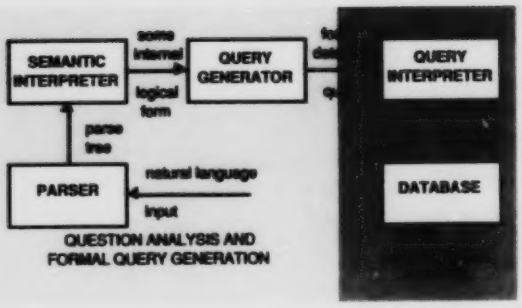


*Figure 1. A typical natural language database system. (from Cercone & McCalla, 1986)*

Mason's questions. Understanding such phrases are particularly troublesome to automate since "police", "expert" and "technician" are all normally nouns. Generalizing semantic considerations for such constructions have proven evasive to date. The compositional approach to natural language understanding favoured by the logic grammarians becomes combinatorially explosive and many researchers have opted to represent noun-noun constructions as single lexical entries instead, thus constraining the computation required to disambiguate noun-noun constructions, and circumventing a annoying semantics problem. When the domain of discourse is well specified and the number of such phrases is small, this approach works adequately. But is this covert procedure generally practical? Consider the noun-noun phrase "western region outage log" employed by telecommunications service personnel. Would the designer of a system designed to automatically process language of this nature resort to separate lexical entries for "southern region outage log", "eastern region outage log", "northern region outage log", "northeastern region outage log", ..., "western district outage log", ..., "western prefecture outage log", ..., "western region service log", ..., "western region outage record", ...?

Imagine further, the processing required by our automated language understanding system to emulate the part of Perry Mason. Not only must the subtleties of language understanding realized by Mr. Dayton be mastered but also the reasoning capabilities of Mr. Mason and extraction of relevant and salient features of the conversation be identified in order to generate the appropriate next question. Actually, Mr. Mason's task is much simpler than Mr. Dayton's - to generate an utterance which conveys a presumably preexisting thought. Mr. Dayton's task as listener is to decide what Mr. Mason must have been thinking in order to motivate his utterance in the particular context in which he uttered it.

Speculating only on this abbreviated introduction, it would appear that the automation of ordinary natural language capabilities using computers is a formidable task indeed. In general, we can say that understanding a natural language is simply a remarkable achievement. By contrast, a natural language interface, say, to a relational database, is simpler to comprehend. Although one ultimately encounters problems comparable to the unconstrained natural language understanding situation, the domain of discourse, and thereby the context, is highly constrained by the database schema. General analysis of language phenomena and much of the ambiguity inherent in natural language understanding is limited. Generating appropriate and natural responses to questions posed to such a natural language database system is a currently popular research intensive endeavour, as we shall see later.

Historically, computer scientists have distributed the challenge of natural language access to a database into two subproblems: the natural language analysis component and the database access component. Questions entered in natural language would be translated into a statement in a formal query language. Once the statement is unambiguously formed, the query would be processed by the database management system in order to produce the required data. These data would then be passed back to the natural language component where generation routines would produce a surface language version of the response. This is the fabled natural language front end paradigm, as depicted in Figure 1.

Once the problem of natural language access to a database has been divided into two activities, investigations of each activity can proceed separately resulting in a conceptual advantage since numerous problems can be ignored. This isolation of activities has resulted in impressive early progress.

Notwithstanding initial successes in this area, the general form of the next generation of natural language database access systems is becoming apparent. In such a system, the user would not question an alien database, but would instead engage in conversation with a friendly, responsive information system. This system's interpretation and generation routines would emulate many of the discourse techniques humans use to communicate with one another. The information access routines would access much more than extensional data, and do so even during the interpretation and generation of natural language. Simply stated, the next generation of natural language "front-ends to databases" will not be front-ends at all, but will be integrated understanding systems, and will not query databases, but will flexibly interface with "knowledge bases". If such an integrated understanding system is to be achieved, a number of important issues must be dealt with. We separate these issues into three general categories: (1) domain knowledge needed to interpret queries, (2) domain knowledge needed to answer queries, and (3) knowledge of the user.

In the next two sections we present a number of concerns which will have to be taken into account, both in the creation of the processes which handle the natural language and the design of the conceptual structures added to the data base to form a knowledge base.

## 2. The need for knowledge to access information

A sophisticated natural language system would require little or no learning on the part of the user who would simply "ask" the database various questions. What would such a natural language system do, and what structures and processes are necessary in order to get a system to do it? To provide some focus to the discussion, we assume that the user is trying to obtain academic advice.

Complexities arise when building natural language capabilities into database interfaces, consider the

sentence:

I want the marks in CS110. [2-1]

Interpreting this query appears straightforward. The sentence structure is simple: almost any parser would easily recognize the subject "I", the main verb "want", and the object "marks", modified by the prepositional phrase "in CS110". It would not be difficult to map the word "marks" onto the corresponding database attribute, and to require that only marks in the course Computing Science 110 be accessed. A list of these marks could easily be produced and returned to the user. Most natural language front-ends could handle this without undue difficulty.

However, many assumptions underlie this interpretation which may not, in fact, correspond to what the user intended. The first problem which must be resolved is how to recognize [2-1] as a question; its surface form is declarative, not interrogative. Presumably recognizing the underlying request speech act is not too difficult for current systems, since almost any input to the database is likely to be a request. We are interested, however, in the next generation of natural language interfaces, where it is possible to imagine the user informing the system of his/her desires ("I want to change all marks of 49% to 50%.", "I want to add something to what I just told you.", etc.). Moreover, other phraseologies are more obscure (for example, "Can you give me the marks in CS110?", where a yes/no answer is inappropriate). The development of computational models which satisfactorily explain how to recognize the underlying user intention despite the surface form of the natural language is well underway, see Cohen (1990).

Recognizing the underlying speech act(s) is just one item which must be inferred about the user. The system needs to know or infer what the user wants with the marks in order to decide what exactly to present to him/her. For example, it is unlikely that anybody wants just the marks; presumably, names and student numbers should accompany them. Moreover, if the user is the registrar, who wants to mail the marks out to the students, it would be a good idea to include addresses with the names. If the user is the university's statistician, it may be sufficient to give the distribution of the marks, rather than the list of students and their marks. Certain types of users may not be even be permitted access to the marks, for example, another CS110 student.

Other unspecified aspects of [2-1] must be clarified if an appropriate response is to be given. Does the user want the marks for all sections of CS110 or just one section? If just one section, might it be possible to infer which section without asking the user, for example, Prof. Smith would want the marks of his own section? Does the user want the marks for last year's CS110 course? Next year's? The course currently underway? If s/he wants the marks of the course currently in progress, should the system hold the request in abeyance and respond at the end of the term when the course is done? How about holding the request if the marks are for next year's course? Once the course and the section are determined, the system still has to figure out whether all marks are required, or just final examination marks, or the final grade for each student. The system must also decide what to do about the request if it is somehow inappropriate. For example, CS110 may not have been offered, or there may not be any course named CS110, or the marks may not have been assigned as yet.

One possible approach to sort out ambiguities like these is to coerce the user to use a formal language where ambiguities don't occur, although it is still possible for some types of ambiguity to arise - the multiple access path problem, see Wald (1985), for example. Learning and retaining the formal language is awkward if the database is accessed by computer naive users. Another possible approach is to engage the user in an (extended) "clarification dialogue" as suggested by Codd et al. (1978). Lamentably, the user is then forced to expend excessive effort simply to make a simple query understandable to an inflexible computer system. This, too, is not likely to impress computer-naive users, and would mitigate against the usefulness of the natural language interface. The salient alternative is to make the natural language interface behave much more like a human, who would use knowledge of the user and of the subject to accurately infer answers to most of the questions raised above.

*Domain Knowledge is Required to Interpret Queries*

There are many situations where it is necessary to use domain knowledge in order to interpret queries. The situation where the domain knowledge need is most evident is when resolving references made in the input query. A particular reference problem which arises in natural language interfaces is that of anaphoric references, especially pronoun references. The following sequence of sentences, e.g., could easily arise in the academic advice domain:

Could I have a report on the students who are registered in Computer Science? [2-2]
Would you summarise it for me? [2-3]
Which students dropped out? [2-4]
Which of them are still mentioned in the report? [2-5]

A natural language system would have to resolve the pronouns it in [2-3] as referring to the concept represented by the report in [2-2], and them in [2-5] as referring to the students in [2-4]. Note that the reference is actually to the answer produced by the system to the user's queries, rather than to the concept in the query itself. A non-pronominal anaphoric reference which must be resolved is the report in [2-5] refers to the report produced in response to [2-2]. There are many other kinds of anaphoric reference possible, some of them much more subtle than these such as the "forward references", see Strzalkowski & Cercone (1986, 1989) for examples.

Another place where the need for domain knowledge is evident is in discovering and resolving ambiguities which arise in the interpretation of a query. Ellipsis frequently occurs during database access,

especially given the tediousness of typing questions rather than verbalizing them. Ellipsis can often be dispensed by syntactic mechanisms. Tracking the focus of attention of the user as he/she asks a series of questions is sometimes important in natural language database interfaces, as the following sequence of queries illustrates:

Who had an honours average last year? [2-6]
Which of them had the highest average? [2-7]
Was there anybody else close? [2-8]

To answer query [2-6], the system must search through the set of all students. In sentence [2-7] the focus is narrowed to the set of students who had an honours average last year. Query [2-8] also assumes a focus set of students with an honours average last year. Note how differently [2-8] would be interpreted if it were asked after [2-6] without the intervention of [2-7] to change the focus set.

*Domain Knowledge is Required to Answer Queries*

Domain knowledge is also required to answer queries, one category of which consists of questions asking about entities which reflect general rules which apply in the domain, rather than entities which happen to be accidentally true of the current data. Even with such general rules, it is not always possible to respond definitively "yes" or "no". Knowledge of any large domain (the kind that might really benefit by being "automated") will not be complete. Facts will be missing, errors will occur in the data, some rules simply won't be known, some topics not covered.

There are several kinds of "ignorance" a system can have. One kind arises when the system does not have all of the facts. Consider the following example:

Have any students ever failed CS882? [2-9]

The system may be able to look back and see that no students have failed CS882 according to its records, but it may also realize that its records only go back three years. Thus, in accordance with the principle of giving the user as much information about its limits as possible, the system should respond with something like "Not according to my records, but they only go back three years" rather than with "No" or "I don't know".

It is important that the system be able to encode knowledge about what it knows and does not know. A related issue is to keep track of exceptions to general rules. For example, to answer the query

Do all professors in the Computer Science department have a Ph.D. degree? [2-10]

the system may find a general rule $(\forall x)(\text{professor}(x) \Rightarrow \text{has-PhD}(x))$ which would allow it to respond "Yes". Such universal rules are fine, in theory, but in knowledge bases representing actual domains, there are bound to be exceptions. Some of these exceptions will represent special cases; others may represent errors in the data. In either case, the system must discover these exceptions and produce an extensive response based on them; for example, "All professors do except Professor Jones". It may prove useful to explain the cause of the exception in order to help the user understand the subtleties of the general rule. Thus, an answer like "All professors do except Professor Jones. She was hired before the requirement that all professors have Ph.D. degrees came into effect" might be more appropriate. If the system is adept at producing such explanations, it may even help the user distinguish exceptions that are special cases from exceptions that are errors in data.

Another place where a knowledge base may be needed rather than simply a database in order to successfully answer a query is in the area of summary response generation. Instead of a long enumerative response to the query "Which courses may a Computer Science student take in addition to the courses in his or her major?" (for example, "Classics 100, Classics 101, Biology 110, ...."), a summarized version of the response (for example, "Other courses in Arts and Science") would be more appropriate. It is fairly easy to imagine how this might be done without recourse to anything beyond a relational database. In this case the database could be searched for all courses taken by computer science students, and then the faculty which offers any non-computer courses read. If the entry for the faculty attribute for each such course is "Arts and Science", then the summary response can be given.

Other considerations requiring domain knowledge to answer queries include hidden time dependencies, for example, "Is professor Jones available for advising" may require a monitored response such as "No, shall I tell you when he is?"; answers related to hypothetical queries, for example, "If I gave Mark an 85% what would the class average be?"; references to system generated concepts, for example, the concept "members of the graduate faculty" may be a system generated concept, subsequently referenced, which answers the query "Who is capable of supervising graduate students"; practical considerations regarding updates; requests concerning the database structure, for example, "Who is teaching which courses this fall?"; and the generation of extended responses.

*Modelling the User is Important as Well*

The need for domain knowledge in order to interpret queries and generate responses is indisputable. In fact, many of the queries used as examples thus far demand that the system be able to infer the intentions of the user in order to interpret what the user is asking for, and hence to produce an appropriate response. Domain knowledge is not sufficient; we also need to model the user.

The database community has long recognized the need for different user views corresponding to different kinds of users. These user views allow the database management system to restrict the kinds of access available to a given class of users. We propose to make similar use of user models. Moreover, a user model would be helpful to disambiguate the user's utterances in several ways: it would restrict the number

of possible interpretations of the user's query; it would generally reduce the combinatorics involved in accessing the knowledge base; and it is far easier to decide how to phrase the response for a class of users, for example, managers may need summary responses, clerks extensional information.

Grice (1975) develops four basic tenets of the cooperative principle which a speaker should obey: (i) the maxim of quantity: be as informative as required, but no more so; (ii) the maxim of quality: make no contribution which is believed to be false or for which adequate evidence is lacking; (iii) the maxim of relation: be relevant; and (iv) the maxim of manner: avoid obscurity of expression, avoid ambiguity, be brief. Grice formulated these principles for human discourse. Much of recent natural language dialogue research has investigated and subsequently developed sound computational support to Grice's maxims. Directly or indirectly Grice's maxims are of central importance to natural language understanding research, see Mylopoulos et al. (1976), Webber et al. (1983), and Allen & Perrault (1980).

One obvious need for user modelling which arises is to recognize presuppositions the user has implied, and correct any false presuppositions if necessary. Kaplan's (1984) CO-OP system was one of the first to demonstrate that presupposition correction was a serious necessity even in the supposedly constrained world of practical natural language understanding. To illustrate, consider the following query:

How many undergraduates passed CS859 last year? [2-11]

There is a presupposition in [2-11] that undergraduates are allowed to take CS859. Evidently, the user believes this presupposition, or s/he wouldn't have asked the question in this fashion. An answer of "None", therefore, does nothing to correct this false presupposition in the mind of the user. The system, therefore, violates the maxim of quality classified above. A much better answer would be "Undergraduates are not permitted to take CS859".

Recognizing the implication of multiple user goals, keeping track of user's knowledge, answering why questions, and making scalar implicatures all demand some degree of user modeling and extended database knowledge.

Clearly, knowledge is needed to access information. We need domain knowledge to interpret queries and to answer queries and we must account for user knowledge in this process also. We propose to continue our investigations into the problems we mention and to incrementally integrate our solutions in successive prototype natural language interfaces to commercial database systems. In particular, two problems for which we have incorporated our results include generating appropriate responses to null database answers resulting from false user presuppositions, Kao et al. (1988), and eliminating the multiple access path problem, see Hall (1986).

We are confident that, without resorting to a sophisticated and wholly integrated knowledge-based system which will be necessary in the longer term, we can construct systems to access information in ordinary language which will prove superior to the limited number of such products currently available. Large investments in commercially available relational databases have been made by industry, government agencies, etc. Providing the tools to access relevant information for the non-specialist is appropriate.

In the next section, we demonstrate how to incorporate knowledge structures into relational databases in order to provide quality responses to null database answers resulting from false user presuppositions. These knowledge structures are completely general and portable, and provide solutions to several other problems mentioned in this section.

## 3. Incorporating Knowledge Structures into the Database

The present generation of natural language database systems emphasize portability, e.g., Kaplan (1984), Davidson (1982), and Grosz et al. (1977), and cooperative responses, e.g., Webber et al. (1983), Kaplan (1984), and Kalita et al. (1986). Most of these systems require a knowledge base of some sort; general knowledge bases appear essential for cooperative response generation. We presented one solution to providing quality responses to natural language queries which arise from null responses in Kao et al. (1988). Space considerations preclude us from reporting those results fully here.

The knowledge base model shown below provides us with a general way of capturing essential information to generate quality responses. Two algorithms given in Kao (1986) further exploit the knowledge base model and demonstrate the quality responses we can generate from the model.

### *The knowledge base model*

Our knowledge base (KB) model consists of metadata information: information about the database structure, such as entity concept hierarchies, generalization and aggregation hierarchies, knowledge about entity relationships, entity relationship constraints, knowledge about null values existing in the database, knowledge about event precedence in the database domain, etc. The knowledge base is a separate component in the natural language database system, see Figure 2. The knowledge base is mod-

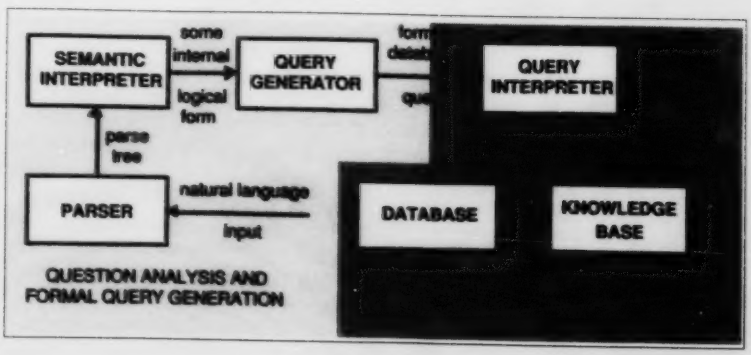


***Figure 2. A natural language database system with a knowledge base component.***

elled on the Relational Model/Tasmania [RM/T], (Codd, 1979).

For relational databases, the knowledge base is inexpensive to incorporate. No special operators are required to manipulate the knowledge base; slight modifications the existing relational operators can be used. The knowledge base is conceptually familiar to database administrators, it is immediately applicable as an add-on to any existing database, and is retrievable via SQL. The knowledge base is easy to implement as a table-driven scheme, thus this approach enhances portability. The model captures intensional meta-data information, with the addition of a static event calendar of the application domain. Our model makes the knowledge base independent of data values in the database. Database updates will have no effect on the knowledge base unless there is a change in the database schema.

The RM/T model distinguishes P-relations (property relations) from C-relations (characteristic relations). Only single-valued functional dependencies are considered in a P-relation; in a C-relation only multi-valued dependencies are considered. Our model does not distinguish between these relations because we can always obtain all of the functional dependency information by consulting the schema. Since we are primarily handling intensional facts in the knowledge base, the model is marginally different from the RM/T model, in which both intensional and extensional facts are handled.

Consider the sample database schema shown in Figure 3. For that schema, additional relations are added to form our knowledge base. There are basically two types of entity handled in our KB model: simple entities and the associative entities. All simple entity types can be found in the ENT-relation, and the knowledge base is closed under all simple entity types, that is, we assume that all simple entities' identifiers are known by the world modelled by the database. For every entity type found in the ENT-relation, we assume that there exists a relation in the database that contains the list of all members of that entity type. The primary key attribute field, which we assume not to be a composite primary key, of a complete list relation (CLR) is naturally taken to be the identifying field of the corresponding simple entity type. Associative entity types are relations which we called AG-relations. Since we allow an associative entity type to be any n-ary relation, an AE-relation is introduced to keep track of all associative entity types that are defined in the domain. Both simple entity types and associative entity types are allowed to have properties. The PG-relation is introduced to bind properties to different entity types.

We use a CLASS-relation and a GH-relation to provide generalization and aggregation hierarchies for entity concepts. The GH-relation allows us to built hierarchical structures on an entity concept, and we can structure an entity concept with respect to different categories (classifications) with the CLASS-relation. Sometimes an entity type, simple or associative, or properties of an entity type might be time dependent. We use the EG-relation and the E-relation to facilitate event precedence relationships. An event can be represented by any attribute field defined in the database, or by an E-relation. An E-relation is a relation which stores information about an event that has some predefined approximate (or exact) dates that are known to the knowledge base. Exceptional cases can also be modelled using the EXC-relation where exceptional case(s) can be attached to different concepts. Finally, the V-relation contains all the view definitions which are defined in the knowledge base model. The key way to tell whether an attribute concept participates in any of the event precedence relation- ships or exceptional facts is to put the corresponding attribute field as a value in the proper relation.

Our knowledge base model contains this package of relations added to the database, see Kao et al. (1988), and the system illustrated in Figure 2 evolves further. Rather than having the knowledge base interact solely with the database, a well-integrated natural language database system shares information among the semantic interpreter, the knowledge base, and the query generator. The task of determining how to integrate these components requires additional research effort.

We now briefly describe our initial portable, KB-based natural language interface, SystemX.

***Figure 3. Database schema.***

OFFERING (CNAME, SEMESTER, CLASS#)
TAKE (CLASS#, SEC, STUDENT#, FINAL-GRADE)
COURSE-PREREQUISITE (CNAME, PREREQUISITE)
CLASS-ROOM (CLASS#, SEC, TIME, ROOM#)
COURSE-PREVIOUS-NAME (CNAME, PREVIOUS-NAME)
INSTRUCTOR (INSTRUCTOR#, NAME, OFFICE, SEX, STATUS)
COURSE-DESCRIPTION (CNAME, DESCRIPTION)
STUDENT (STUDENT#, NAME, MAJOR, MINOR, SEX, STATUS)
SEMESTER (SEMESTER#, YEAR, SEASON)
DEPT-CHAIRMAN (DEPT#, CHAIRMAN, FACULTY)
CLASS-DEPT (CLASS#, DEPT, UNITS)
DEPT-FACILITY (DEPT#, FACILITY)
TEACH (CLASS#, SEC, INSTRUCTOR#, TEXT)
FACULTY-DEPT (INSTRUCTOR#, DEPT)

## 4. SystemX

Our English to SQL translator, SystemX, has been successfully implemented at Simon Fraser University in COMMONLISP. SystemX integrates a number of advances in natural language interface research with several unique improvements in a single system. The result is an interface which is portable, highly modular, and flexible.

### *A Precis of SystemX*

SystemX discovers the grammatical type and meaning of certain natural language terms simply by using their form. The morphological processor can recognize the grammatical category and root form of many words by analyzing the inflectional endings of those words. Thus storage requirements and the requirements for processing time to update the lexicon are reduced. The utility of this feature was first noted by Damerau (1985). This acquisition enhances the capa-

bility of SystemX to be transported to other systems.

Underlying the translation to SQL is the PATHFINDER subsystem for generating join paths given a set of two or more column names. Since terms are treated as values in the database, the representation of an expression of two or more terms or expressions is the join path between them. The task of the interpreter is to pass the column names represented by the terms in an expression to this system and build up a representation using the join path, which it returns. If the database scheme is non-trivial, there may be more than one possible join path involving a given set of attributes. Thus Pathfinder must solve the multiple access path problem (MAPP) problem, cf. Wald and Sorenson (1984). Work by Hall (1986) has addressed this part of our prototype system. Treating semantic interpretation in this way results in a very flexible system which requires little customization.

SystemX appears to handle quantification better than other systems. Multiple quantifiers such as "do only math majors take every math course?" present little difficulty. To usefully serve as a front-end to databases, SystemX must be able to correctly interpret quantifiers such as 'every', 'all', 'only' and 'some' into the appropriate database operations. Some systems such as INTELLECT, derived from ROBOT (Harris, 1977), cannot handle quantification at all. Others, such as that produced by Natural Language Inc. can handle only limited use of quantifiers.

SystemX provides an extensive quantification capability, handling all English quantifiers. Unique among natural language understanding systems, SystemX is able to handle combinations of quantifiers within a single query. A sample query, "Has every math major taken math344?", illustrates the complexity of the problem. SQL has no direct means of representing the universal quantification expressed by 'every math major'. Instead, the query is translated by a series of negated subqueries which state that if a student can be found whose major is math and who has not taken math344, respond 'No'. The SQL code generated for this query is illustrated below.

```
ctr
    select a.student#
    from student a
    where a.major = 'math'
      and not exists (select *
        from class b, offering c, enroll d
        where       b.offer# = c.offer#
          and       c.cname = 'math344'
          and       a.student# = d.student#
          and       b.class# = d.class#
          and       882 > c.semester
```

This last example "Who has received the highest grade in math344?" demonstrates the ability of SystemX to compute values and use the value as part of a selection. The prepositional phrase 'in math344' is included in the clause which computes the highest grade and in the clause which selects the students who receive that grade. (See Listing 2)

Recently we have replaced the parser of SystemX.

```
select distinct d.student#, c.final-grade, c.numeric-equiv, b.class#, a.class#,
a.offer#, a.semester
  from offering a, class b, grades c, enroll d
    where  a.cname = 'math344'
      and  a.offer# = b.offer#
      and  c.final-grade = d.final-grade
      and  b.class# = d.class#
      and  883 > a.semester
      and  c.numeric-equiv = (select max (h.numeric—equiv
        from enroll.e, class.f, offering.g, grades.h
          where e.class# = f.class#
            and f.offer# = g.offer#
            and g.cname = 'math344'
            and d.final-grade = h.final-grade
```

***Listing 2***

The grammatical formalism we chose is that of Head Driven Phrase Structure grammar, Pollard and Sag (1987), which uses unification (Shieber, 1986) as its primary control mechanism. HPSG was chosen for several reasons. HPSG places grammatical power in the lexicon rather than rules. The current implementation of HPSG (McFetridge, 1990) contains only seven grammar rules. Extending the coverage of the grammar consists of building the lexicon, not adding more rules.

HPSG is not a theory of syntax, but a theory of sign, a theory of the relation between sounds (or graphemes) and meaning. Thus, attention has been paid to how semantics fits in the theory, although we have not implemented the semantics outlined in Pollard and Sag (1987).

HPSG is not yet a fully specified theory. Only four grammar rules are specified in Pollard and Sag (1987) and problems such as binding and control are not addressed. Thus, we see our work on the implementation of a parser based on HPSG as a contribution to theory development.

A significant gap in Pollard and Sag (1987) is the coverage of binding. A serious natural language interface must be able to handle phenomena associated at least with question formation and relative clauses. Binding is established by nonlocal features introduced by lexical items. For most lexical items, the value of a binding feature will be empty. Special lexical items which have no phonetic/graphic content are established as gaps. The head features of a gap are inherited from the subcategorization list of the head daughter and are also established as nonlocal binding features. These nonlocal features are inherited by subsequent phrasal signs until a filler which unifies with these features is encountered.

In the original SystemX, translation of a parse tree to SQL was effected by a set of rules which took database representations of lexical items and based on their content and the syntactic rule which created the parse tree built a representation of the database operation corresponding to the linguistic expression. As an example, the phrases math student and math major might both represent a projection on the student# attribute of those tuples in the student relation which have math as the value of the major attribute.

This structure would later be converted to a SQL statement selecting tuples from the student relation and possibly joining them with tuples from other relations on the student.i.# attribute. Control over which translation rules applied was governed by the syntactic rule which parsed the phrase. Each semantic rule was associated with one or more syntactic rules. Conversion to HPSG has eliminated this control, as the rules of HPSG are few and general. Instead, translation rules are keyed to the grammar rule together with the head features of the daughters. Retaining the translation rules from the original version of SystemX has allowed us to retain an existing system which is tailored to the task of representing queries to relational databases.

## 5. Generating Appropriate and Natural Responses

There are two ways in which natural language interfaces facilitate the interaction of end-users with databases. By enabling them to pose their queries in natural language, interfaces camouflage the complexities of formal query languages from the user. In addition, interfaces employ natural language as a medium to express responses to user queries, thus consummating the naturalness of the interaction.

It is common to conceive of the response returned by a database system as a table, a list, or other fixed-format layout. However, demands placed on the system for conciseness, naturalness and intelligibility argue in favour of natural language as a primary medium of response generation, with tabular format to be used only when appropriate, rather than as default.

Early database interfaces used "canned text" to generate English answers. Their response-generators used natural language more or less as a syntactically-cosmeticized variant of their formal responses, and failed to take full advantage of the quality of response generation and the overall quality of man-machine interaction provided by natural language. Experience with early interfaces has sharpened our notions of what constitutes a good response, as well as revealed the potential of natural languages as media of effective interaction with databases and intelligent systems.

In recent years we have witnessed a considerable surge of interest and progress in the theoretical and engineering aspects of natural language generation and man-machine interaction. Consequently, more natural language interfaces to databases are incorporating mature natural language generators to communicate with their end-users.

We consider three situations in which researchers have had vested interest in natural language generation in the context of natural language database systems:

1. *response generation:* natural languages are used to express the content of knowledge-structures (logical forms, relational tables, etc.) retrieved from the system as a result of processing the query.
2. *paraphrase of query into natural language:* while natural languages are favoured for their intelligibility, they often introduce problems due to their inherent ambiguity. Such ambiguity, coupled with the unambiguous nature of formal query languages, means that it is quite likely for some natural language queries to have two or more interpretations in the formal query language. In instances where such ambiguities are detected, it may be better for the system to re-express its interpretation of the formal query in natural language, and confirm with the user whether that is what the user meant by his/her query.
3. *mature dialogue:* in order to avoid problems due to ambiguity or misconceptions, the system may be required to elicit more input from the user. Moreover, if the user finds the response inadequate or unclear, (s)he may want to post follow up queries to the system in order to obtain an acceptable response. In such situations, a one-shot response generator is hardly adequate; what is needed is a mature dialogue facility.

*Criteria for the generated natural language expressions/utterances:*

Several factors or criteria of quality are involved when generating a response. Satisfying these criteria has implications for many different aspects of response generation, and consequently, for a number of components of the interface as well as for the underlying system. We consider the following factors:

*Valid:* The response should be correct and informative. In many cases, generating a valid response is addressed as a conceptual task of the underlying system rather than as a linguistic task of the interface.

*Grammatical:* The response should be grammatically correct, and should not mislead or confuse the user by violating linguistic constraints.

*Easy to understand:* The response should be easily readable. It should not be a mere syntactic variant of a formal response, as may be procured through "canned text" or fortran 'format' statements.

*Appropriate:* Validity, coupled with intelligibility, requires the response to be appropriate in the context in which it is generated.

Appropriate responses harmonize with Grice's maxims. Although stated in general terms and not sufficiently precise to suggest designs for interfaces in themselves, Grice's maxims provide suggestive guidelines for deriving useful criteria and their design implications. Conforming with Grice's maxims requires the generated response to blend well with ongoing dialogue. In other words, the response should be customized or "tailored" to the context.

The communicative context of response generators include, among other things, due consideration of the system's communicative goals, a model of the user, and the dynamic linguistic context defined by the preceding conversational turns. An appropriate response would be acceptable on the basis of purely linguistic- or discourse considerations as well as on the basis of its sensitivity to other knowledge sources such as the system's communicative goals and user model. User models may contain knowledge about several aspects of diverse groups of users of the system: knowledge about the user's domain knowl-

edge, knowledge about the kinds of syntactic constructs and words that are appropriate for communication with the given type of user, and so on.

Generating an appropriate response thus has far-reaching effects on most modules of the response generator: content selection, discourse structuring, choice of syntactic structures, and lexical choice.

*Coherent:* For the response to blend well in context, it is required to be coherent in terms of discourse- and linguistic constraints: devices such as pronouns and ellipses should be used properly and in ways they are used in natural human dialogues. Proper discourse connectives or rhetorical devices should be used to signal shifts of discourse variables: like change of topic ('by the way'), continuation of the discourse sequence ('and then'), contrast ('on the other hand'), and so on.

*Efficient:* The response generation process should be computationally and linguistically efficient.

*Co-operative:* Often, it is not desirable to generate a curt, optimal response to the query. We should provide more information than what the literal interpretation of the query warrants.

Cooperativity is widely recognized as a desirable feature for natural language interfaces. We devote the remainder of this section to discuss cooperative response generation.

*Cooperative response generation*

A cooperative response, by definition, aims to satisfy the needs of the user (questioner) as well as possible. Not all user needs can be recovered from an analysis of the query alone. Based on a number of factors, like the profile of the user (as represented in the user model) and the history of the on-going dialogue, the generation system should assess the implicit needs of the questioner, and accordingly, prepare its response. It is worth noting that a cooperative response may have to flout Grice's maxim of quantity, since it could contain more information than a direct response in minimal context would contain.

The importance of cooperative responses in natural language interfaces was noted by Kaplan (1984). Cooperative response generation is an active and interesting area of research in the intersection of logic databases and natural language processing, as may be discerned from the research of Gal & Minker (1988), Amsili et al (1990) and Gaasterland & Minker (1991).

The generation component of a natural language interface makes decisions at several levels in order to prepare a cooperative response. We now examine briefly how cooperativity occurs at several levels of response generation, and how the user model is a significant determinant of the cooperativity of responses.

*Content determination:* At the strategic or planning level, the system must determine the content of the response. Cooperativity requires that this task be guided by the user model. Ignoring user considerations at this level can not only cause a response generation which is not sufficiently informative, but is also misleading or confusing to the user and inhibits the user's participation in the dialogue.

*Discourse structuring:* Organizing the content of the response into a coherent presentation is as important as the task of determining the content. Arbitrary orderings of sentences in a paragraph do not lead to acceptable or coherent text. The knowledge for organizing responses coherently and cooperatively is best incorporated into the response generation system by representing knowledge about how humans organize their utterances into coherent discourse. A module of discourse knowledge in a cooperative response generation system would consist of schematic patterns of discourse commonly employed by humans, mechanisms for attaching information content into units of discourse patterns, and finally, generating coherent natural language sentences out of this organization.

*Sentence generation and lexical choice:* Often, in natural language sentences, not all the information conveyed is implicit. Speakers take advantage of contextual factors and presuppositions, and thereby leave some information implicit, assuming that the hearer can recognize the presuppositions and recover the information that is not overtly conveyed through the words of the sentence. A natural language response generation, in order to achieve naturalness of its output sentences, can similarly take advantage of presuppositions and other factors and leave some of the information implicit. However, cooperativity requires that the decisions on explicit vs. implicit expression of information should be regulated by the user model: standard unregulated use of patterns based on general patterns in human usage may 'take the user for granted' and fail to be cooperative.

Natural languages are rich in conceptual information; most databases are not. Most of the typical large-scale databases in use do not contain enough conceptual information about the relationships between objects in the database. In order to generate an appropriate and natural response, sufficient knowledge about the underlying conceptual structure should be available. This, combined with the portability criterion for the interface dictates that a domain model must be built for each distinct database. If the database is organized for efficient updating, storage and retrieval, it may not be in a shape which is correlated or compatible with the conceptual structure of the domain it covers.

## Concluding Remarks

We presented a myriad set of problems categorized for easy future reference for designers of natural language processing systems. We then pointed to how to include a knowledge base into such systems and described SystemX, our initial database interface. We are proud of SystemX because we have made exciting advances to the state-of-the-art for natural language interfaces to databases. SystemX also adds to progress in natural language understanding. Since templates permit definition by recognition, lexicon storage reduction is an accomplishment. Our morphological component obviates the need to store words which are regularly inflected,

etc.

SystemX achieves greater portability than previous systems. The semantic representation is a fully specified representation of the database structure and no customization is necessary to translate it into the query language. Transportation among SQL databases is easier. Transportation to other database management systems is possible.

Of course problems remain and challenges abound. With respect to SystemX and its successors, we have both short term objectives which we are confident can be done relatively easily and longer term ones which form the basis of our challenge for the expert information management systems of the future. We constantly wrestle with knotty little problems which make this work interesting. We expect we will continue to wrestle with them for some time.

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## Acknowledgements


The authors are members of the Institute for Robotics and Intelligent Systems (IRIS) and wish to acknowledge the support of the Networks of Centres of Excellence Program of the Government of Canada, the Natural Sciences and Engineering Research Council, and the participation of PRECARN Associates Inc. We are also grateful to Canadian Cable Labs Fund for their financial assistance and to the Simon Fraser University Centre for Systems Science for the use of their facilities.

# A Wafer Scale Dynamic Thermal Scene Generator

G.H. Chapman, M. Parameswaran and M.J. Syrzycki

*The production of Wafer Scale Transducer Arrays (WSTA) is enabled using a combination of post fabrication processing technologies. Previously wafer scale digital integrated circuits were successfully built using post fabrication laser interconnection techniques. Micromachining technology has generated many sensors via anisotropic etching of prefabricated CMOS chips. As a prototype WSTA a wafer scale Dynamic Thermal Scene Generator is being developed, to generate a controllable infrared image for use in calibrating IR detector arrays. The basic array consist of two cell types, one being a thermal pixel, containing a poly Si resistor sitting on a suspended oxide bridge. The second cell contains the addressing, intensity register, and current level control electronics. Significantly, unlike digital WSI designs, WSTA redundancy efforts must emphasize local over global transducer sparing even considering cluster defects. Granularity in transducer location (allowed variation in physical position for desired emissions) drives local pixel cells into creating small sub-transducer arrays, with multiple devices at each site turned on for a single pixel. The control cells are allowed a larger substitution area than the thermal transducer.*

## Introduction

A new large area device application has been suggested by the combination of two post fabrication processing technologies. Previously wafer scale integrated circuits have been successfully built using laser interconnection techniques after semiconductor fabrication[1,2]. At the same time micromachining technology has generated several sensors using anisotropic etching of prefabricated CMOS chips[3,4]. Combining these techniques has suggested a new concept: the production of Wafer Scale Transducer Arrays (WSTA). Potential applications include: mapping variable distributions within an environment, injecting controlled energy matrices into mediums, mixture of several different transducers types within small physical area including combinations to generate signals and measure the results, plus self healing/repair for reliability.

It is important to note that for traditional WSI the usage of such large wafer area is not directly desired. Instead WSI is an outcome of the need to build complex systems that cannot fit within regular chip areas due to the current limitations of circuit density. Wafer Scale Transducer Arrays are one application where the actual large area of the device is in of itself often desirable. Sensor WSTA's can map the matrix of some variable's distribution within an environment onto a very small position scale for applications such as process control. Emitter WSTA's enable the injection of a controlled matrix of energy (mechanical, thermal, acoustic etc.) into the environment engendering the creation some desired condition within a medium with a fine position control. This paper will explore the design and implementation work done to date on one WSTA: a Wafer Scale Thermal Pixel Dynamic Scene Simulator (WSTPDSS). The development of this device is preceding both as a potential real application, and as a prototype of the whole WSTA concept. The progress made in that design to date will be covered.

## A Wafer Scale Thermal Pixel Dynamic Scene Simulator (WSTPDSS)

The creation of sub-millimeter sized thermal spots and the generation of a continuously changing two-dimensional thermal scenes using thermal spots are

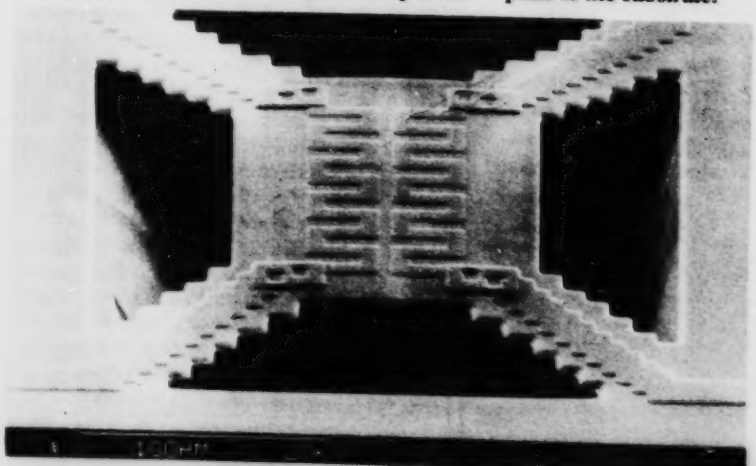

***Figure 1: Micromachined thermal pixel. The oxide plate is suspended above the etch pit generated by the anisotropic etching. Two poly silicon resistors sit on the plate, and are connected to current source via metal lines that cross the bridges from the plate to the substrate.***

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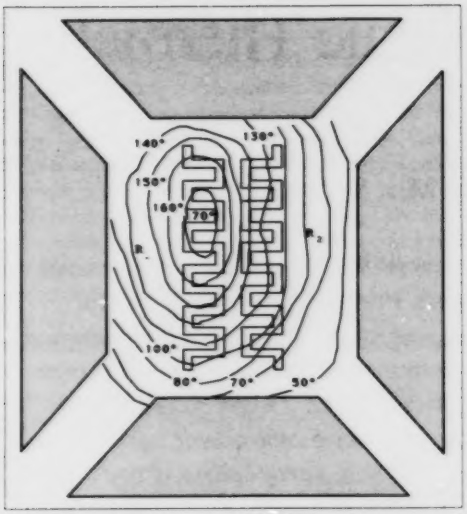
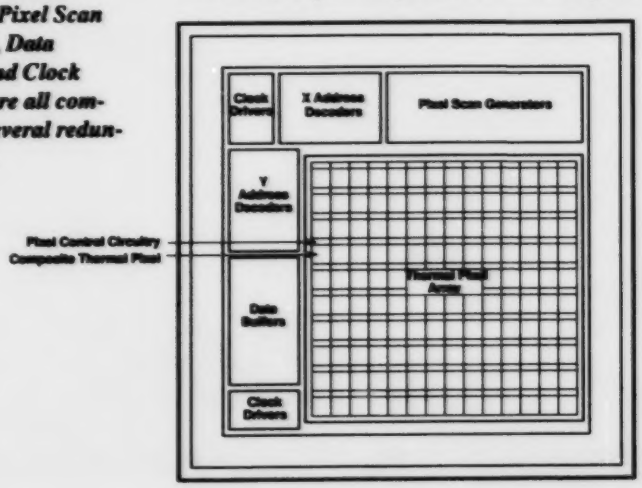



***Figure 2: Isothermal temperature distribution of a thermal pixel. Note that WSTA thermal pixels would use only one poly resistor, not the two illustrated here.***

essential to calibrate complex IR optical systems used in research, medicine and military applications. Conventional Thermal Resolution Test Targets (TRTT) and Dynamic Scene Simulators (DSS) are physically large and lack resolution[5]. Therefore, fabrication of miniature heater elements using the planar microelectronic processing technology and silicon micromachining techniques were adopted[6]. Since the silicon microelectronic process is the most popular IC fabrication technology today, there exists a possibility to integrate the heater filaments and the support circuitry to perform the DSS. However, many proposals to build such an Integrated Thermal Dynamic Scene Simulator involve customized fabrication facilities to integrate the IC process and the silicon micromachining process. This would involve setting-up of an expensive fabrication facility, exclusively designed for this purpose.

An alternate process has evolved from the development of a CMOS compatible thermal picture element. This thermal pixel is a heat conduction isolated heater filament capable of generating a local hot-spot (see Figures 1 and 2 for an example made on a "Silicon Foundry" multichip project wafer[6].) This small black body emitter produces elevated temperatures creating emission of radiation in the IR submillimeter wave band. In addition by digitally controlling the heater's current it has the capability of producing a range of IR intensities (thermal grayscale). The thermal pixel in CMOS technology consists a polysilicon heater filament sandwiched between the field oxide and the CVD oxides. To fabricating the operational thermal pixel a simple maskless post processing anisotropic etch can be performed. The oxide layers inherently present in the CMOS wafer will themselves not only act as a mask, but also form part of the mechanical structure[3]. The most commonly used silicon anisotropic etchant is simple wet etch using a chemical popularly known as EDP, a mixture of ethylenediamine, pyrocatechol and water[4]. Exposed to EDP the various silicon crystal planes etch at different rates with the (100) plane (the surface orientation of most IC's) being removed about 30 times faster than the (111) plane (this ratio depends on several processing factors)[4]. For the square oxide opening of the thermal pixel on a prefabricated chip an EDP etch results in four inward-slanting (111) planes (at 54.7 degrees to the top surface) forming the walls of the pit. As the oxide layers are not significantly attacked by the post-processing etchant, the undercutting of the silicon below the mask creates suspended structures or plates with no additional masking steps. Also note that CVD oxide films cover the regular circuits formed by the CMOS process on the same chip, thus protecting them from the EDP etching. The important point is that the cavity within the silicon underneath the sandwiched polysilicon heater filament creates the desired thermal isolation for a black body. The heat isolation is sufficient that a pixel can be made incandescently glow with about 4 mA of current. However the lifetime of the pixel is relatively short (about half an hour) at such high levels due to oxidation of the poly silicon. For the target system the desired temperatures are much more moderate (100-200 degrees C), and the currents lower, and lifetimes appear to be extensive. The intensity of the emitted radiation follows a black body relationship, and is proportional to a $T^4$ relationship (where T is in degrees Kelvin). The simple heat flow calculations for the isolated poly resistor show that T is proportional to the resistive power loss, or $I^2R$. Approximations show that for moderate T values near room temperature the radiant IR intensity varies with the $I^{0.5}$. However, the actual current value for a given IR gray level is a function of the details of the pixel design's heat flow to the substrate.

***Figure 3: Floorplan of the wafer scale thermal pixel array. Note that the blocks on the wafer edge (X,Y Address Decoders, Pixel Scan Generator, Data Buffers, and Clock Drivers), are all composed of several redundant cells.***




The proposed design for the Wafer Scale Thermal Pixel Dynamic Scene Simulator thus is a WSTA that requires only a single anisotropic etch of silicon substrate after wafer fabrication. It contains an array of thermal pixels emitting infrared energy accompanied by a control circuitry necessary for a thermal scene simulation. Fabrication of several thermal pixel designs and small-size arrays of thermal pixels with control circuitry has occurred using a standard 3 micron CMOS technology on Canadian Microelectronics Corp. multichip project wafers, which were

subjected to the anisotropic etching. Figure 6 shows a second generation structure, with control circuitry. Test results are proceeding towards optimizing the system building blocks and to initiate design of wafer scale thermal pixel array.

The key to any successful wafer scale system is the development of a procedure to substitute spare cells for failed circuit elements. Wafer Scale Transducer Arrays operate under one significant restraint not applied to digital WSI that considerably affects the redundancy/defect avoidance schemes. In regular WSI the physical position of a substituted cell is often restricted only by the ability to divert signals from the inoperable circuit block and route them to the spare ones, with some additional limits on the delay time generated by the new path. By comparison for WSTA's the granularity in location (allowed variation in physical position of a spare transducer) depends on the application but generally is very limited. Inherently this pushes WSTA's towards local sparing, where the substitute cell is a nearest neighbor of the failed one, and away from global sparing, where the replacement block may lie nearly anywhere on the wafer. This emphases the importance of separating the transducer cell from the processing/control electronics block. With careful design the processing/control block can have nearly global sparing capability.

Thus, as the pixels have a fixed location, a good first approach to defect avoidance for the Wafer Scale Thermal Pixel Dynamic Scene Simulator uses a "hard wiring" method, such as Lincoln Laboratory's laser linking process. This employs the power of a laser to make a physical, low resistance connections between metal bus lines, and also to segment the bus paths, to route signal to working devices and avoid defective ones[1,2]. The particular structure to be implemented on the WSTPDSS is a fully CMOS compatible structure known as the laser diffused link[1]. The proven success of the laser link makes it the best alternative for near term experimentation with the WSTPDSS design.

Implementing this architecture for the Wafer Scale Thermal Pixel Dynamic Scene Simulator creates the floor plan consisting of several blocks shown schematically in Figure 3. In system design it operates like a memory mapped display with each pixel containing an intensity register. The periphery of the wafer contains X and Y physical addressing decoders, clock drivers and data bus buffers. The pixel intensity data is loaded in parallel into the data buffers that places it on a wafer wide data bus, where the addressed element latches it into the thermal pixel's display register. This data represent the magnitude of a current flowing in each pixel and, thereby, an intensity of thermal energy radiated from each pixel to surrounding media. The present design uses 4-bit intensity data to program 16 gray levels of thermal energy, but in general any number of bits can be chosen accordingly to the needs. A pixel scan generator controls the thermal scene displayed by the array and drives a turn-off/turn-on scheme for all pixels. Clock drivers are responsible for the synchronized flow of data to data registers associated with particular pixels. Multiple copies of the above blocks are built-in, providing global redundancy necessary for Wafer Scale implementation.

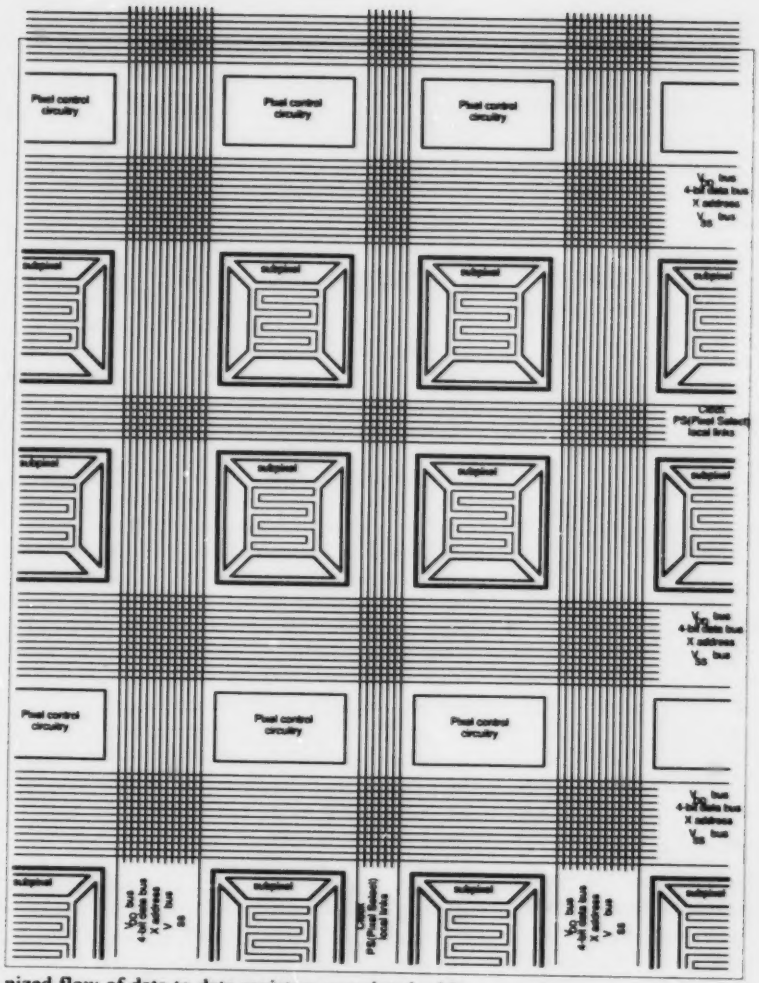



*Figure 4: Structure of a composite thermal pixel with control circuitry and buses featuring 50% local redundancy. This should be taken as a diagrammatic illustration, and is not to scale. In practice the subpixels would be all evenly spaced in both X and Y directions, and the pixel control more spread out in area.*

In WSTPDSS's the majority of circuit area is consumed by the array of thermal pixels interleaved by buses linking all components of the system. The size of the array is much larger than the size of target display being attempted. Figure 4 shows each thermal pixel is composed of a 2 x 2 array of subpixels, two identical blocks of pixel control circuitry, and a set of buses. For a working pixel two of subpixels and one control circuitry block are required, generating an overall 50% local redundancy. All the subpixels are location on equally spaced grid points, though the size of the x separation and y separations need not be the same. In the cell harvesting process all thermal pixels will be tested and the proper area for the highest yield subarray of thermal pixels will be identified. The exact row and column subpixel pairs needed for a given pixel address are fixed by the choice of the physical pixel origin point. However that can shift within a considerable number of subpixel rows and columns to generate the maximum area of pixels with perfect yield (see Fig. 5).

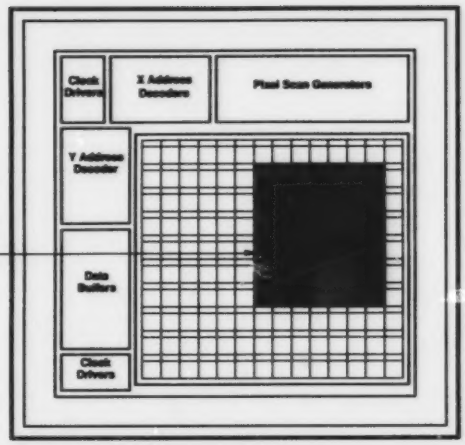
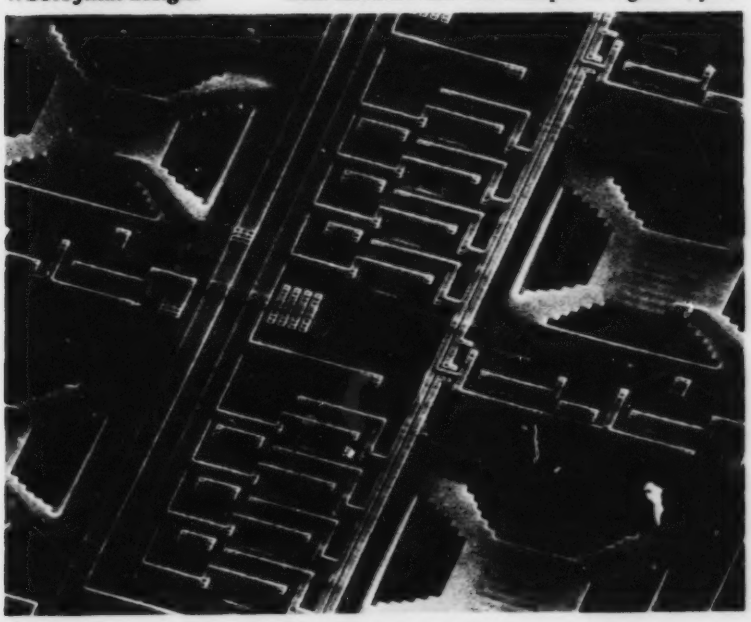



***Figure 5: An example of possible location of Thermal Pixel Scene subarrays corresponding to different defect distributions. This also illustrates how the emission scene may be moved around to compensate for defects that develop over time.***

A more global sparing of pixel control circuitry between neighboring pixels are feasible due to location of pixel control blocks between rows of thermal pixels, thus each control block can be laser-linked with either the top or bottom row, and right or left columns of thermal pixels. Figure 7 shows also a local redundancy of Vdd, Vss, clock, data, pixel select, and address buses. Among those Vdd and Vss buses feature the largest redundancy due to relatively high current levels delivered to turned-on subpixels.

Figure 7 shows a few examples of the WSTPDSS layout to visualizing the flexibility of the design in local sparing of transducers and driver circuits. Since any combination of two subpixels can be utilized as one composite thermal pixel, many forms of defect avoidance are possible. Note how choosing two subpixels out of the cluster of four for a composite pixel allows the structure to alleviate the problem of small-area local defects (spot defects). Note also the redundancy in control circuitry also permits to laser-link control blocks from one pixel site with subpixels from different site. For example in Figure 7, pixel control circuitry from the (i+1,k-1)th location has been used for two subpixels from the (i,k-1)th site. Such links will help avoid larger defects that may wipe out a few neighboring transducers or control blocks, while still maintaining a proper position of transducers in the array. The X, Y address select lines programmed for the pixel control circuitry are those of the physical address of the pixel itself, not of the control section.

***Figure 6: A first version of an implemented Thermal Pixel with adjacent control circuitry. This is a test vehicle and not the WSTA final design.***



While the wafer scale aspect of WSTPDSS has yet to be implemented, experimentation has begun on the control circuitry for the thermal pixels. As noted before Figure 6 shows a 3 micron CMOS first implementation of a digitally controlled thermal pixel. The revised schematic diagram of the circuitry, as modified for use with each subpixel, is shown in Figure 8. The pixel driver (Figure 8.a) used six MOS FET's (M1-M6) in a current mirror configuration and four transmission gates controlling the output current. The M1 transistor sets up the current in the M2 transistor, which is mirrored by the transistors M3 to M6 with the gain factors changing from k to (a**3)k, respectively. The coefficient "a" represent the current increment on the 4-bit scale. Transmission gates connected between the M2 transistor and gates of driver transistors M3 - M6 are driven by data signals D0 - D3. They turn-on and -off the driver transistors, thus converting the 4 bit data into the proper magnitude of current flowing to the thermal pixel, implemented as a polysilicon resistor Rload onto a silicon dioxide micromachined membrane. The currents are controlled by the size of the transistors, which are calculated using SPICE models. Exact thermal modeling of the subpixel heat flow determines the 16 current levels to obtain a linear intensity range. In the wafer scale implementation the control circuit associated with every pixel (see Figure 8.b) includes four 3-input NAND gates that latches the intensity word into data register for storage. From here, data controls the drivers' transmission gates when pixel select (PS) is activated. The relatively high current draw of each working subpixel means that not all elements can be emitting at once. Hence, the Pixel Select signal comes from the Pixel Scan Generator and its variable duration enables different scanning schemes for thermal pixel simulation. It is the scan generator that controls the physical origin point of the displayed pixels. Data can be written to the pixels while they are activated for display. Since all working pixels will be harvested, if the area of perfect yield exceeds the target system then the ability to shift the display origin point creates some ability to substitute working pixels for those that fail at the periphery. In either any case the area with the maximum number of working cells can always be chosen.

## 3: Current and Future Implementations

The sections above described the full Wafer Scale Wafer Scale Dynamic Thermal Scene Generator. Current research has concentrated on the design and fabrication of the subelements of this system in CMOS 3 micron technology by Canadian Microelectronics Corp. plus 2 micron MOSIS multichip projects. After fabrication they undergo the anisotropic etch-

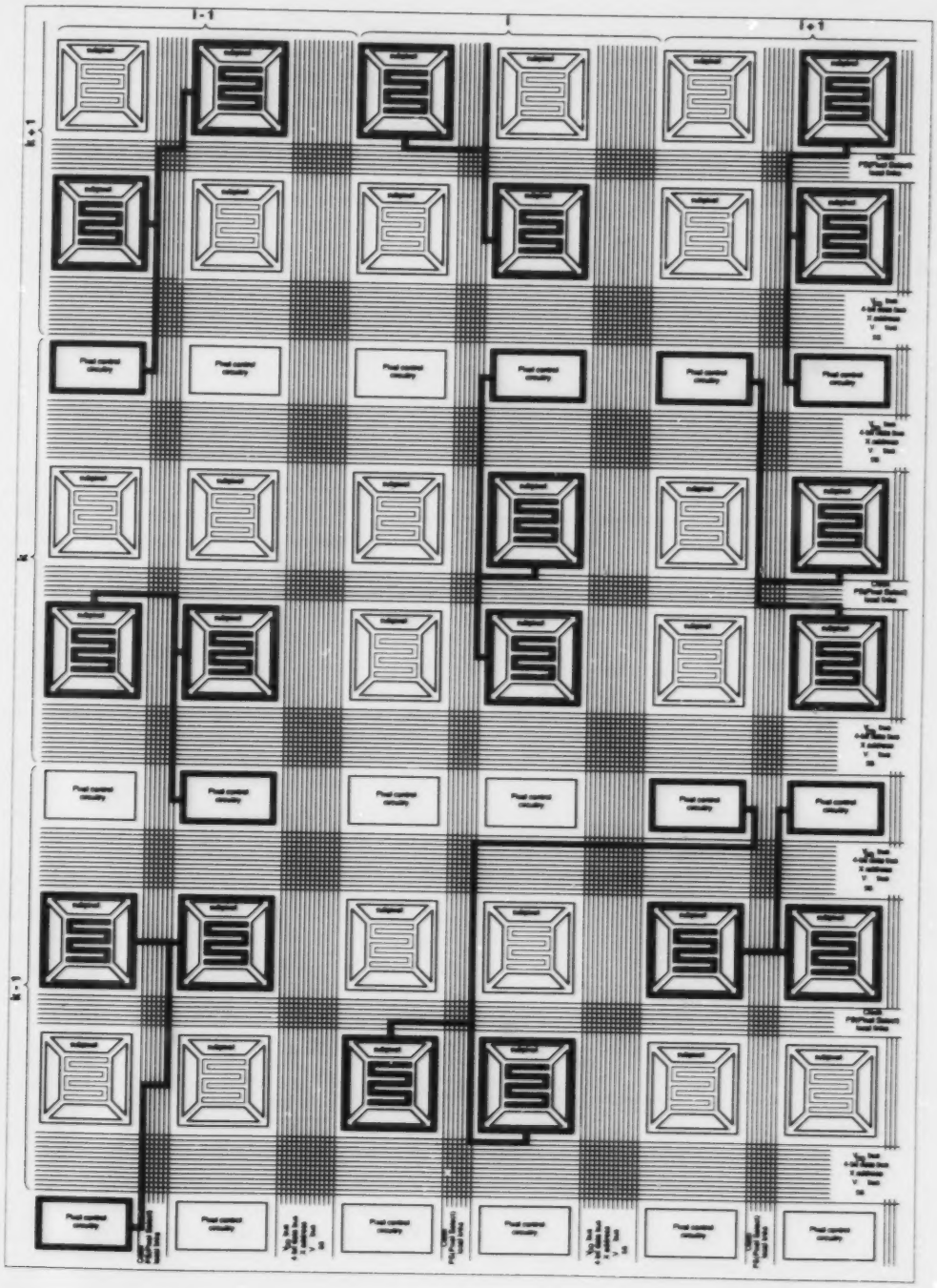


*Figure 7: Examples of sparing transducers and control circuits within a wafer scale thermal pixel array. Note that while the shape of the full pixel changes, they are confined to specific row and column pairs.*

ing in our micromachining and sensor laboratory. The current prototype versions are undergoing testing, with other designs submitted for fabrication. Laser linking test structures have also been submitted in the same technologies. At the same time experiments are being done on the wafer scale aspects of the thermal pixel EDP etching. EDP has been used to etch large structures before and the issues here are ones of process control and pixel yield. After proving the individual elements the plans are to test out a chip sized array of the thermal pixels and control circuitry, with all the good components being laser-linked to produce a usable small thermal pixel array. Experiments on the redundancy scheme, and control circuitry action are planned. At that point all the information should be available to determine the feasibility of a Wafer Scale Dynamic Thermal Scene Generator.

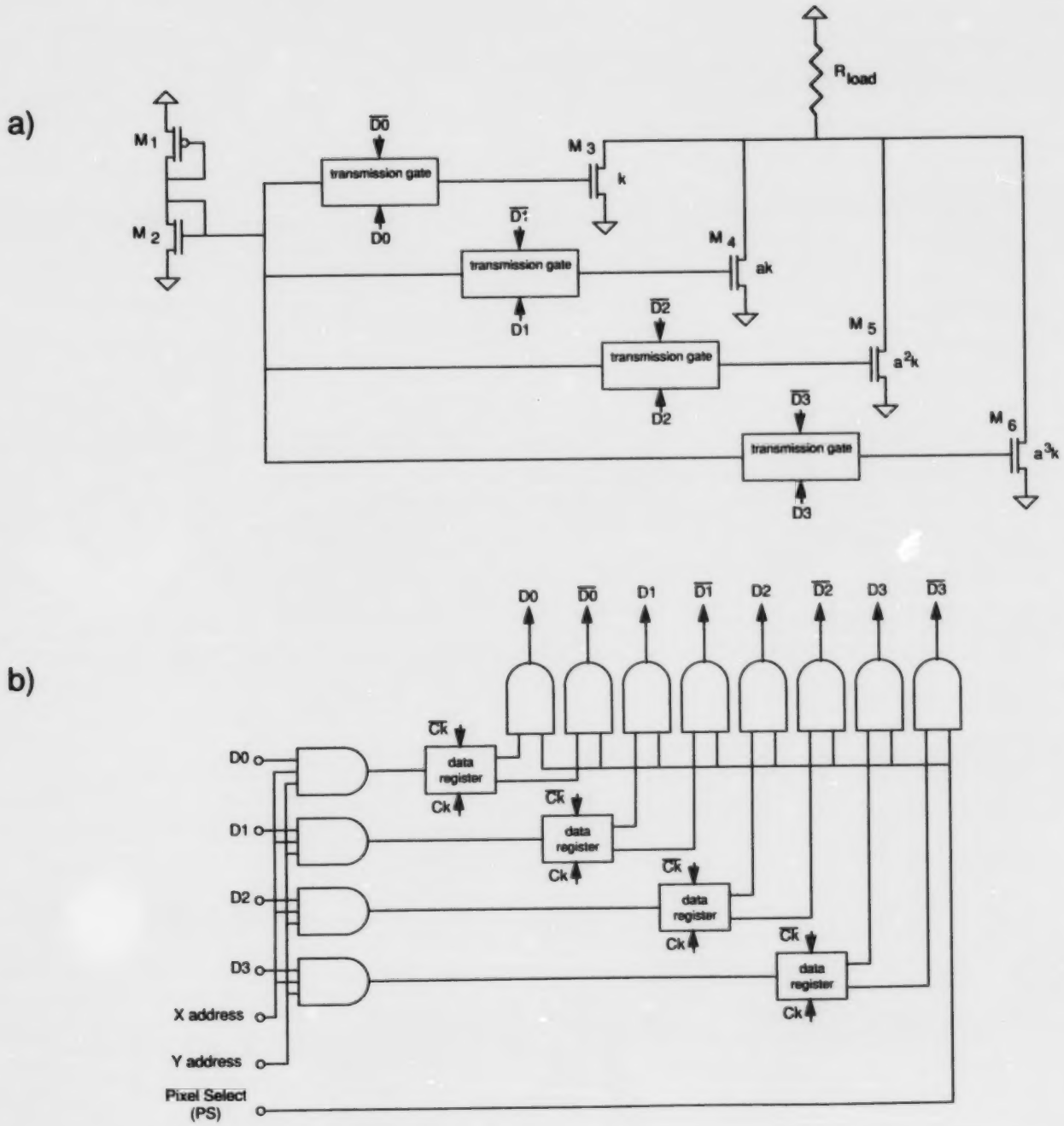



***Figure 8: Schematic diagram of a thermal pixel driver (a) and a control circuit (b) used for each thermal pixel in the wafer scale thermal pixel array.***

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# Obstacle Avoidance with Resource Constrained Detection

John S. Bird and Martie M. Goulding

*This paper describes resource constrained detection in the context of obstacle avoidance sonars. The key concept, that available resources and mission objective should determine the operating point of the sonar, is contrasted with classical approaches to decision theory. It is shown that resource constraints are employed in real world implementations whether or not they are recognized as such and therefore should be accounted for in the original design. Through a simple example it is shown how an AUV's obstacle avoidance capabilities can be related to the sonar's characteristics through resource allocation.*

## Introduction: The concept

Signal detection theory has come a long way since its early beginnings in the late 1940's. Mathematical advances in the field of hypothesis testing and engineering advances in radar and sonar have resulted in systems that can detect and track targets at farther and farther ranges. Statistical sensor deployments, which necessarily involve decision theory, are still plagued, however, by the same three difficulties outlined by Middleton in 1960 [1], namely, the apparent arbitrariness of cost assignments, the inadequacy of the a-priori information, and the uncertainty in the choice of an optimality criterion. These difficulties are a direct result of working in the real world where we cannot avoid paying the price for ignorance. The resource constrained detection theory outlined in this paper is a unique approach to the fusion of classical decision theory and real world problems.

Resource constrained detection is best described by way of example and although this example is not that of an obstacle avoidance sonar, its simplicity better helps to communicate the concept. Consider a system consisting of a gun control radar and a gun designed to protect a ship. Assume the gun is capable of firing one round per second and is assigned the task of destroying all incoming targets. We would like to design a system that has the highest probability of intercepting the targets. A typical strategy to accomplish this is to set the radar threshold to yield a given false alarm probability and shoot at any target that crosses that threshold. This strategy results in a firing rate that is acceptable provided no targets are present and the false alarm rate is less than the maximum firing rate. As targets appear the firing rate increases until, if the number of targets is large enough, targets are missed because the gun is busy. This is a classical overload condition that puts the ship in jeopardy. To reduce the potential for overload the radar false alarm rate is lowered. But this reduces the radar's ability to detect small targets even when the number of targets is small and there is no danger of an overload; so again the ship is vulnerable.

It is clear that in this simple example the degree of protection is determined by the firing rate of the gun and therefore the gun should be fully utilized. The radar should simply direct the gun to the radar cells most likely to contain targets, subject to the rate of the gun. This is a resource constrained detection system where the resource is the gun's firing rate.

The threshold for the radar is easily set to keep the gun busy but not overloaded. There need be no appeal to probability distributions etc. to calculate false alarm rates. If no targets are present the threshold drops to keep the gun firing, albeit at nothing. But the radar is very sensitive to small targets and therefore the ship is optimally protected. As the number of radar cells crossing the threshold increases so does the threshold and therefore the cells most likely to contain targets are passed to the gun. It is shown in section 2 that the detection probability for this strategy is always greater than or equal to that of the strategy first described.

## The Classical Approach

In the classical approach to detection theory the likelihood function plays a central role. It is beyond the scope of this paper to develop the arguments supporting the use of this function and therefore the reader is referred to the excellent books by Middleton[1] or Poor[2]. The essence of the detection problem is that a signal is received and a test statistic developed. (A test statistic is a random variable that tends to be large if a target is present and small if it is not.) If the test statistic is above an assigned threshold a target is declared present; otherwise no target is declared. Classical detection theory assigns a value to the threshold that depends on the probability distributions of the test statistic and the prevailing optimization criterion.

There are a number of criteria that are employed to set the threshold in detection systems. We will discuss the most common one used in sonar systems, the Neyman-Pearson criterion, and compare it with the resource constraint criterion.

The Neyman-Pearson criterion is the one that is employed in the radar/gun example given above. After deciding on an acceptable false alarm probability ($pf$), one uses the probability distribution of the test statistic under the assumption of no targets present to calculate the corresponding threshold. There are a number of

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difficulties with this approach. First, the definition of an acceptable false alarm probability is likely to prove elusive. As we saw in the example, setting pf high will cause the system to overload with the presence of only a few targets. On the other hand, setting it low lowers the sensitivity of the system to small targets even when the system is not busy with large ones.

On the positive side, the Neyman-Pearson criterion does provide an objective means of setting the threshold, without regard for probability distributions, assuming one can actually measure pf. Unfortunately, observing (and therefore measuring) pf is not always possible. One has to make sure there are no targets present and typically wait for a long time if *pf* is to be set to a low value.

Nonparametric hypothesis testing[2] is one approach to detection system design that helps alleviate some of the above problems. Nonparametric detectors seek to make the decision process less sensitive to prevailing statistics by creating a test statistic that is more robust in the sense that it depends on a general characteristic of the distributions. For example, the distribution of the test statistic might be required to be an even function under the target present and absent hypotheses. The essence of this approach is that having admitted our ignorance, we proceed to develop test statistics for which we know the distributions, and then develop optimum tests based on these known distributions. These tests are seldom optimum in the sense that if we knew the distributions of the original data we could do better. But we don't and therefore must be satisfied with the resulting suboptimum performance, which often is adequate.

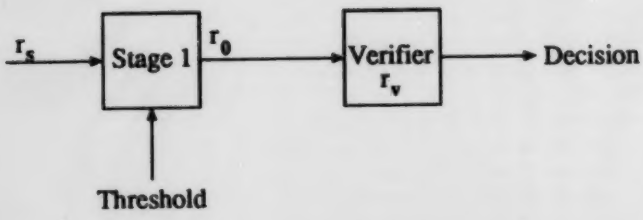
Even with nonparametric tests we have a problem, however. Once the statistics of the test statistic have been decided upon we still have to use a Neyman-Pearson or other criterion to set the threshold. This approach has resulted in the many nonparametric CFAR (constant false alarm) techniques that are available to detection systems designers today[3].

Nonparametric tests do not, however, remove the basic problem with the Neyman-Pearson test, namely the setting of the false alarm probability. We no longer have to measure it because we know what it is, but we still have to set it to some value. For example, in the radar/gun illustration given above we could set the false alarm rate but still not have optimum protection for the ship.

### Rate Constraint (something different)

The remainder of this paper discusses rate constrained detection (a restricted form of resource constrained detection) and applies it to a simple obstacle avoidance problem. Section 2 formally introduces rate constraint detection in the context of a sonar followed by a verifier. The verifier serves as a rate-limited resource for this discussion. It is shown that the rate constraint detection criterion is optimum and out performs the Neyman-Pearson criterion in this practical context. In section 3 rate constraint is applied to an obstacle avoidance problem where it is shown that it maximizes the probability of mission success. Finally, section 4 discusses some of the broader implications of this research and future directions of study.

***Figure 1. A two-stage detection system.***




## 2: Neyman-Pearson and Rate Constraint Criteria

In this section we consider a simple detection system consisting of a sonar (first stage) and a verifier (second stage) as illustrated in figure 1. The verifier is a second detection device which is more sensitive (better performance) than the first but much slower. As illustrated in the introduction, however, (and later with the obstacle avoidance system) the second stage could be a rate constrained resource. The verifier operates at a maximum rate $r_v$ and the first stage operates at the sonar rate $r_s$. We are interested in the system detection probability (i.e. the product of the detection probabilities for the two individual stages). However, we assume that the verifier's performance is independent of both the rate of cells presented to the verifier and the target concentration, $\pi$ ($\pi$ is the a priori probability of a target being present in a given cell). Therefore, our primary task in this section is to investigate the first stage, and we will arbitrarily assume, without loss of generality, the verifier to be perfect. That is, if a detection cell is passed to the verifier as a candidate for having a target, the verifier will confirm or deny the target with no errors. The verifier could also be a resource such as the gun considered in the introduction.

The probability of detection for this two stage system is therefore the probability that a target cell is passed to the verifier. If the first stage were removed the cells passed to the verifier would be chosen randomly and the resulting probability of detection would be

$$pd = r_v / r_s \qquad (1)$$

The purpose of the first stage then, is to match the sonar rate to the verifier/resource rate in such a way that the probability of detection is a maximum and hopefully greater than (1).

### First Stage Detection Criterion

The goal of the first stage is to screen the sonar cells in such a way that detection performance is optimized. In other words, the first stage must choose those cells most likely to contain targets, to pass on to the verifier. Another way to view the problem is that the verifier is a resource that must be utilized in the most efficient fashion to detect targets in the sonar space.

Two criteria for the first stage will be considered, the Neyman-Pearson and the rate-constraint criterion. The Neyman-Pearson criterion, even though suboptimal in this application, is considered because it provides valuable insights into the detection problem. The rate-constraint criterion is optimal for this problem and therefore is investigated in detail.

The primary purpose of the first stage is to match the sonar cell rate $r_s$ to the verifier cell rate $r_v$. The output rate $r_o$ of the first stage can be described in terms of the probability of detection *(pd)* and false alarm *(pf)* of the

first stage as follows

$$r_o = [\pi pd + (1 - \pi)pf]\, r_s \qquad (2)$$

We require $r_o \le r_v$ or

$$\pi pd + (1 - \pi)pf \le r \qquad (3)$$

where $r = r_v / r_s$ is the normalized verifier input rate. Since the verifier's detection probability is independent of the performance of stage 1, we want the first stage to maximize *pd* subject to constraint (3).

Before discussing the two detection criteria it is helpful to briefly describe the constraint in terms of the standard ROC (receiver operating characteristic) diagram. Figure 2 illustrates the linear constraint boundaries (equation (3) with equality) for various values of $\pi$. For $\pi = 0$ we have the vertical line intersecting the *pf* axis at $pf = r$ and for $\pi = 1$, the horizontal line intersecting the *pd* axis at $pd = r$. For $0 < \pi < 1$ the boundaries are a series of straight lines all passing through the point $pf = pd = r$ as shown. Any test developed must have a rate that is less than or equal to *r* and therefore *pd* must be less than or equal to the boundary value for a given *pf* and $\pi$. For example, given values of $pf = pf_0$ and $\pi = \pi_0$ we have $pd \le pd_0$. These constraint boundaries help to describe an operating point for the test criteria.

### The Neyman-Pearson Criterion

The Neyman-Pearson criterion maximizes *pd* subject to the probability of false alarm being less than or equal to a constant, say $\alpha$. The resulting optimum procedure is a randomized likelihood test [2]

$$\delta(x) = \begin{cases} 1 & \text{if } f_1(x) > \eta f_0(x) \\ \gamma(x) & \text{if } f_1(x) = \eta f_0(x) \\ 0 & \text{if } f_1(x) < \eta f_0(x) \end{cases} \qquad (4)$$

where $\delta(x)$ is a decision rule describing the test and $\eta \ge 0$ and $0 \le \gamma(x) \le 1$ are such that $pf = \alpha$. Also, *x* denotes the test statistic random variable, $\gamma(x)$ is a randomizing function, and $f_0(x)$ and $f_1(x)$ are the probability distributions of *X* under the null and alternative hypothesis respectively. For a given test statistic, this decision rule yields a probability of detection that is a function of *pf*, say $pd = g(pf)$, that may be plotted on the ROC diagram as shown in figure 3.

Unfortunately, for most practical systems, ignorance of the exact forms of $f_0(x)$ and $f_1(x)$ must be assumed and therefore $\eta$ can only be determined by indirect means, if at all. Since *pf* is not observable without the a priori knowledge that there are no targets present, dynamic adjustment of $\eta$ to give a desired *pf* is not possible. Therefore, in practice, a Neyman-Pearson decision rule is difficult to construct.

As a result of the practical difficulties associated with the Neyman-Pearson test, system designers sometimes resort to controlling the hit rate which is the false alarm rate only when no targets are present. Such a procedure leaves the issue of optimality (in terms of detection performance) in question. In fact, this is precisely the rate-constraint criterion which we will discuss later.

Our objective here is to investigate the Neyman-Pearson criterion in light of the rate constraint forced on the test by the verifier and expressed in (3). If $\eta$ is set such that $pf = pf_{NP}$ then the hit rate for the test is given by

$$\pi\, pd_{NP} + (1 - \pi)pf_{NP} = r_{NP} \qquad (5)$$

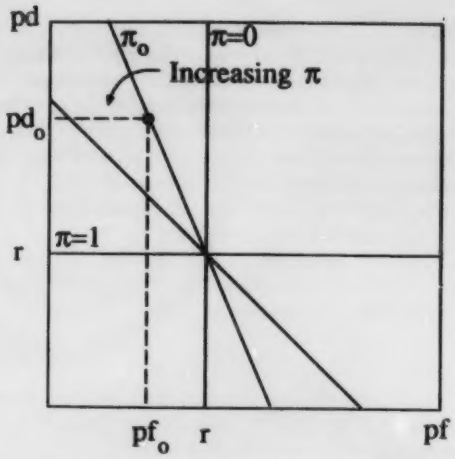



***Figure 2. Constraint boundaries for various values of $\pi$.***

As long as $r_{NP} \le r$, constraint (3) is satisified. If $\pi$ and *pd* are such that $r_{NP} > r$ then the hit rate must be randomized to bring it down to *r*. This simply means that a fraction of the hits are thrown away and not passed to the verifier. Denoting the fraction of hits not thrown away as $\beta$, we have

$$\beta = r / r_{NP} = r / [\pi pd_{NP} + (1 - \pi)\, pf_{NP}] \qquad (6)$$

and the effective probabilities of detection and false alarm are

$$pd'_{NP} = \beta pd_{NP} \qquad (7)$$

and

$$pf'_{NP} = \beta pf_{NP} \qquad (8)$$

Solving (8) for $\beta$ and substituting it into (7) we have

$$pd'_{NP} = \frac{pd_{NP}}{pf_{NP}} pf'_{NP} \qquad (9)$$

In summary, there are two expressions for the probability of detection under the Neyman-Pearson criterion and which one is valid depends upon the fraction $\beta$.

$$pd'_{NP} = \begin{cases} pd_{NP} & \beta \ge 1 \\ \dfrac{pd_{NP}}{pf_{NP}} pf'_{NP} & \beta < 1 \end{cases} \qquad (10)$$

where $pf'_{NP}$ is given by (8). Figure 3 illustrates these relationships on the ROC diagram.

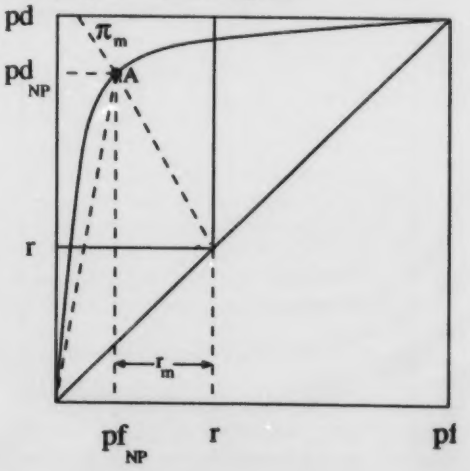



***Figure 3. A ROC diagram illustrating the performance of the Neyman-Pearson test modified to operate under a rate-constant.***

As long as the target population, described by $\pi$, is such that $\beta \geq 1$, the Neyman-Pearson test operates at point A. If the target population increases, however, *pf* and *pd* are forced to drop to maintain the rate at *r*. This drop is described by (10) for $\beta < 1$ and is represented by the straight line from $(pf_{NP}, pd_{NP})$ to (0,0) on the ROC diagram. Therefore if the verifier is overloaded ($\beta < 1$) and random selection is necessary, performance degrades until finally for $\pi = 1$, $pf_{NP} = r$.

To guard against entering the overload region a rate margin $r_m$ can be introduced. The rate margin is defined as the difference between $pf_{NP}$ and *r*:

$$r_m = r - pf_{NP} \tag{11}$$

If $r_m$ is positive the test will admit a certain target population $\pi_m$ before going into overload. If $r_m$ is negative the test is in overload for all $\pi$.

The behavior of the Neyman-Pearson criterion described above is familiar to designers of practical systems who work under a hit-rate constraint. We now discuss the optimum rate-constraint test.

### The Rate-Constraint Criterion

The rate-constraint criterion maximizes *pd* subject to the normalized hit rate being less than or equal to a constant *r*. A rate constrained detection rule is defined as a decision rule having this property. The following proposition is proved in the appendix of Bird[4].

**Proposition 1** *For a hypothesis test between $H_0$ (the null hypothesis) and $H_1$ (the alternative hypothesis) where $f(X=x|H_0)=f_0(x)$ and $f(X=x|H_1)=f_1(x)$ we have the following.*

1. *Optimality: Let d be any decision rule satisfying $\pi pd(d) + (1-\pi)pf(d) = r_1 \leq r$ and let $\delta$ be any decision rule of the form*

$$\delta(x) = \begin{cases} 1 & \text{if } f_1(x) > \lambda f_0(x) \\ \gamma(x) & \text{if } f_1(x) = \lambda f_0(x) \\ 0 & \text{if } f_1(x) < \lambda f_0(x) \end{cases} \tag{12}$$

*where $\lambda \geq 0$ and $0 \leq \gamma(x) \leq 1$ are such that $\pi pd(\delta) + (1-\pi)pf(\delta) = r$, then $pd(\delta) \geq pd(\delta)$.*

2. *Existence: For every $r \in (0,1)$, there is a decision rule $\delta_r$ of the form of (12) with $\gamma(x) = \gamma_0$, a constant, for which $\pi pd(\delta_r) + (1-\pi)pf(\delta_r) = r$.*

3. *Uniqueness: Let $\delta'$ be any r rate constrained decision rule for $H_0$ versus $H_1$. Then $\delta'$ must be of form (12).*

Therefore a rate-constrained decision rule is a likelihood ratio test similar to the Neyman-Pearson test but with a possibly different threshold ($\lambda$ instead of $\eta$). In fact if the a priori probability of a target being present, $\pi$, is zero, the rate-constrained decision rule and the Neyman-Pearson decision rule are identical. However, for higher target densities the tests are different with the rate-constrained decision rule yielding the greater probability of detection.

The rate-constraint decision rule does not have some of the nice mathematical properties of the Neyman-Pearson decision rule because the rule changes for different targets and target concentrations; however, it does have one major advantage. Unlike the Neyman-Pearson rule, the constraint variable for the rate-constraint rule is observable. The constraint variable for the Neyman-Pearson rule is the probability of false alarm which is impossible to observe unless one is sure that there are no targets present. On the other hand the hit rate is observable and therefore can be employed to control the detection process through a feedback loop. This is why hit rate control is used in practical systems and therefore why it is important to be able to make statements about the performance of rate-constrained tests.

The performance of the rate-constrained rule on a ROC diagram can be seen on figure 4. If we assume that a control mechanism is in place to adjust the hit rate then the system operating point will move along the *pd*/*pf* curve until it intersects with the constraint line that corresponds to the target density. The operating point will remain stationary until the target density or the statistics change.

For example, consider operating point *A* of figure 4. If, say the signal to noise ratio drops from $\sigma_A$ to $\sigma_B$ while the target density remains constant, the operating point will move along the rate constraint line to *B*, with an accompanying decrease in *pd* and increase in *pf*. Note that $pd_B$ is higher than would have been obtained ($pd_{B'}$) if the false alarm were maintained at $pf_A$. On the other hand, if the operating point were *A* and the target population increased while the snr remained constant at $\sigma_A$, the operating point would move to *C*. At *C* both *pd* and *pf* are reduced from their values at *A* to compensate for the higher density of targets so the following stage will not be overloaded. Conversely, if the the population concentration decreases, *pd* and *pf* increase thereby increasing the detection sensitivity of the stage.

We define the detection context of a target as the set of all those parameters which influence the position of the operating point. In mixed target and variable clutter situations these parameters may be difficult to identify but the operating point is still easily determined by observing and controlling the hit rate. In these complex situations it may not be easy to translate the operating point into a performance number such as the probability of detection but at least the system is controllable.

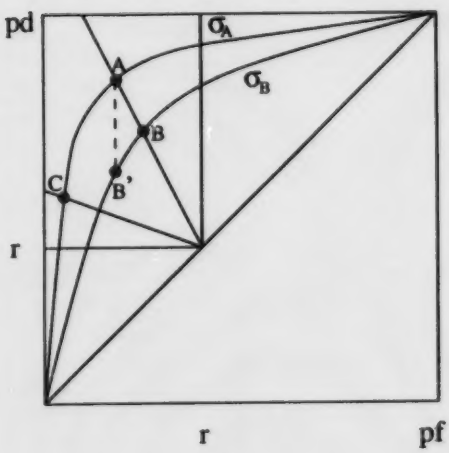



***Figure 4. ROC curves and rate constraint boundaries for two values of snr. ($\sigma_A > \sigma_B$)***

### Comparison of Rate-Constraint and Neyman-Pearson Criteria Under a Rate Constraint

As was discussed in the previous section the modified Neyman-Pearson test (modified to perform under a rate constraint) does not perform as well as the rate-con-

straint test. Specifically,

$$pd_{RC} \geq pd_{NP} \quad (13)$$

The equality holds when $pd_{RC} = pd_{NP}$ for the given detection context which occurs say at point *A* in figure 5. If $\pi$ decreases then the operating point for the RC test moves up the *pd/pf* curve, say to the point where $\pi = \pi_B$. The detection probability $pd_B$ is necessarily larger than $pd_{NP}$ from the proposition on the rate-constraint decision rule. It is also evident from observing that at the new operating point we have another Neyman-Pearson test with a larger *pf* than $pf_A$ and therefore $pd_B > pd_A$.

If the operating point is at *A* and $\pi$ increases then the rate-constraint operating point will move to say point *C* consistent with the constraint curve corresponding to $\pi_C$. Now this is an overload condition for the Neyman-Pearson test and so the operating point for this test must change to point *C'* as described earlier. The operating point *C'* is at the intersection of the straight line from $(pf_{NP}, pd_{NP})$ to (0,0) and the constraint line for $\pi = \pi_C$. We already know that $pd_C \geq pd_{C'}$ because of the proposition on the rate-constraint decision rule; furthermore, by observing the ROC curve we also see that it is true if

$$pd_C / pf_C \geq pd_{NP} / pf_{NP} \quad (14)$$

for all possible points *C* on the *pd/pf* curve. Since this is both a necessary and sufficient condition for $pd_C \geq pd_{C'}$ we conclude that (16) must be true for all ROC curves developed using the likelihood ratio. It can be seen that this is merely a restatement of the well-known concavity of ROC curves[5].

### 3: Obstacle Avoidance Sonar Application

In the last section we saw that because of the rate constraint on the verifier, the Neyman-Pearson criterion for setting the threshold in a likelihood test did not maximize the probability of detection. On the other hand the rate constraint criterion did maximize the detection probability and, in addition, could be implemented in practical situations. In this section we apply the rate constraint detection criterion to the problem of obstacle avoidance for an autonomous underwater vehicle (AUV). We assume that the vehicle must navigate through a field of obstacles with average concentration $\pi$. In other words, $\pi$ is the probability of a particular sonar cell containing a target. Also it is assumed that the sonar starts to collect information on a particular cell (i.e. starts building the test statistic) as soon as the cell comes within range of the sonar. When the cell is a certain distance away, called the decision distance, the sonar must decide to avoid the cell or not.

If the vehicle encounters *k* cells on its way through the field then the probability of a mission success (i.e. probability of not bumping into an obstacle for *k* independent cells) is

$$p(success) = (1 - \pi)^k \quad (15)$$

If a sonar with an obstacle detection probability of *pd* is added to the vehicle then probability of success increases because the only obstacles that will stop the mission are those that are missed by the sonar. Since the probability of not detecting an obstacle is (1- *pd*), we have

$$p(success) = (1 - \pi(1-pd))^k \quad (16)$$

Therefore the effect of the sonar is to reduce the target concentration by a factor of (1-*pd*). This increases the mission success probability. In fact, as *pd* increases to one the mission success probability also increases to one.

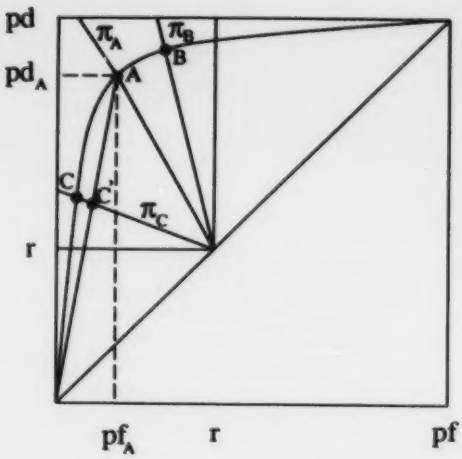



***Figure 5. Comparison of the modified Neyman-Pearson and rate constrained tests.***

There is a price to be paid, however, for the higher mission success probability. Every time an obstacle is detected by the sonar, the vehicle must manoeuvre around it, thus delaying its arrival at the assigned destination. We will assume that the vehicle is capable of a top speed of $v_o$ m/s and that it must travel at an average velocity of $v_a$ m/s ($0 < v_a \leq v_o$) in order to meet the mission requirement. Therefore there are two ways that the mission can fail, impacting an obstacle or arriving late. The first is mitigated by a higher *pd* but this aggravates the second. The second is mitigated by maintaining $v_a$ regardless of the obstacles which, of course, increases the likelihood of hitting an obstacle. Hence we must risk the vehicle to maintain $v_a$ and our task is to minimize this risk. We will show that the rate constraint detection criterion does this.

The detection performance of the sonar is related to the mission objective by first obtaining a relationship between the vehicle's velocity and the threshold crossing rate of the sonar. If the vehicle is travelling at the required average velocity, $v_a$, then the sonar cell rate (the rate new cells are presented to the sonar) is

$$r_a = v_a / d \quad (17)$$

where *d* is the range extent of a cell. The average velocity of the vehicle may be expressed in terms of the fraction of time the vehicle spends in manoeuvre mode and transit mode assuming that it travels at $v_o$ when in transit mode. Therefore

$$v_a = v_o (1-f) + (d / t_o) f \quad (18)$$

where *f* is the fraction of time in manoeuvre mode and $t_o$ is the time it takes to manoeuvre around an object. In other words, the vehicle travels at a velocity of $v_o$ when it is transiting and at an effective velocity of $d/t_o$ when it is manoeuvring around an object.

The average time spent manoeuvring out of a total time *t* is $r_a t t_o$ where $r_a$ is the average threshold crossing rate. Therefore $f = r_a t_o$. But $r_a = r r_s$ where *r* is the normalized rate; hence $r_a = r (v_o / d)$ from (17). Therefore the fraction of time spent manoeuvring is

$$f = (r v_a t_o) / d \quad (19)$$

Substituting (19) into (18) and solving for *r* we obtain

$$r = d (v_O - v_a) / v_a (v_O t_O - d) \quad (20)$$

Therefore, given a sonar resolution cell size *d*, a maximum velocity $v_o$, a manoeuvre time $t_o$ and a mission specified average velocity $v_a$, we can deter-

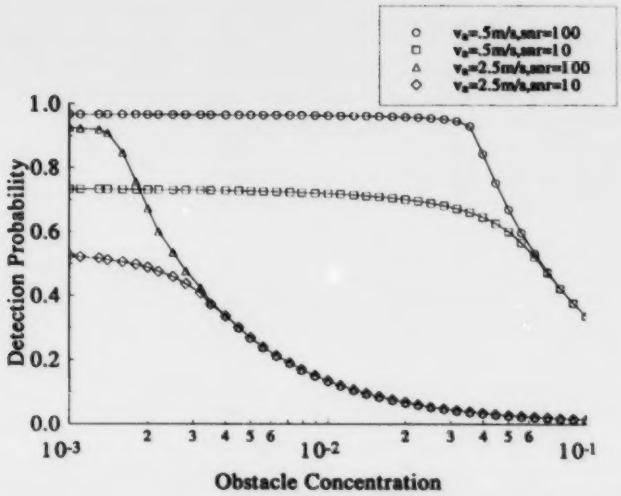



***Figure 6. Detection Performance of rate constraint criterion under various snr and average velocities.*** $v_a$***=3m/s,*** ***d=10cm.***

mine a required threshold crossing rate. If this rate is exceeded the vehicle will spend too much time in manoeuvre mode and will not meet the mission deadline. If the rate is less than *r* the vehicle will arrive ahead of schedule but will be exposed to a greater than necessary risk of hitting an obstacle.

This is a rate constrained detection problem for which the constraint of equation (3) holds, namely

$$\pi pd + (1-\pi)pf \le r = \frac{r_a}{r_s} = \frac{d\,(v_d v_a)}{v_a (v_d v_a\, d)} \qquad (21)$$

Since this problem fits the rate constraint scenario described in section 2, we know that the rate constraint criterion will be optimal. To be definite in our results and to provide an example, let us assume that we are detecting Gaussian targets in Gaussian noise (i.e. Rayleigh fading targets in Rayleigh noise) where we have the following relationship[6]

$$pd = pf^{1/(1+snr)} \qquad (22)$$

where *snr* is the signal-to-noise ratio. It should be noted that this model typically is used to describe the test statistic that results from the coherent integration of a single sonar return over time. A more accurate model for our problem would be one that employs noncoherent integration from pulse to pulse as the cell of interest moves closer to the vehicle. This model, however, does not have a neat closed form expression for *pd* as a function of *pf* and therefore would not be efficient for showing the trends we wish to show. Since the purpose of this paper is to illustrate principles rather than model particular signal statistics we have chosen to use the mathematically simpler model here. Results for the more accurate model are not expected to be significantly different anyway.

For the rate constraint criterion, which satisfies (3) with equality, we have

$$\pi pd_{rc} + (1-\pi)\, pd_{rc}^{\,1+snr} = r \qquad (23)$$

where $pd_{rc}$ is the detection probability using the rate constraint criterion. Therefore to determine the maximum *pd* attainable, namely $pd_{rc}$ that satisfies the mission velocity constraint we must solve the above transcendental equation.

For the Neyman-Pearson criterion we have

$$r_{NP} = \pi pd_{NP} + (1-\pi)pd_{NP}^{\,1+snr} \qquad (24)$$

where $r_{NP}$ is the threshold crossing rate. Remembering that the threshold *h* is chosen to provide a specific false alarm probability $pf_{NP}$, $pd_{NP}$ is fixed through equation (22). Therefore as long as $r_{NP} \le r$, we maintain *pd* at $pd_{NP}$, but if the target concentration increases so that $r_{NP} > r$, $pd_{NP}$ must be reduced by the factor B (as discussed in section 2) to maintain our desired velocity $v_a$. Hence for the Neyman-Pearson criterion we have an effective probability of detection $pd'_{NP}$ as described by equation (10). Since we have

$$\frac{pd_{NP}}{pf_{NP}}\,pf'_{NP} = \frac{pd_{NP}}{pd_{NP}^{1+snr}}\,\frac{\pi pd_{NP}^{1+snr}}{\pi pd_{NP}+(1-\pi)pd_{NP}^{1+snr}} = \frac{r}{\pi+(1-\pi)pd_{NP}^{snr}} \qquad (25)$$

equation (10) becomes

$$pd'_{NP} = \begin{cases} pd_{NP} & \text{if } r_{NP} \le r \\ \dfrac{r}{\pi+(1-\pi)pd_{NP}^{snr}} & \text{if } r_{NP} > r \end{cases} \qquad (26)$$

By comparing equations (23) and (26) we are able to verify that $pd_{rc} \ge pd'_{NP}$. First consider $r_{NP} \le r$; then we have

$$\pi pd_{NP} + (1-\pi)pd_{NP}^{\,1+snr} \le \pi pd_{rc} + (1-\pi)\, pd_{rc}^{\,1+snr} \qquad (27)$$

for which we require $pd'_{NP} = pd_{NP} \le pd_{rc}$. Second, for $r_{NP} > r$ we have

$$\pi pd_{NP} + (1-\pi)pd_{NP}^{\,1+snr} > \pi pd_{rc} + (1-\pi)\, pd_{rc}^{\,1+snr} \qquad (28)$$

for which we require $pd_{NP} > pd_{rc}$, but for this condition we have

$$pd'_{NP} = r / [\,\pi + (1-\pi)\, pd_{NP}^{\,1+snr}] \qquad (29)$$

and by rearranging equation (23) we see that

$$pd_{rc} = r / [\,\pi + (1-\pi)\, pd_{rc}^{\,1+snr}] \qquad (30)$$

and therefore $pd'_{NP} < pd_{rc}$. Hence $pd_{rc} \ge pd'_{NP}$ for both conditions as expected.

In figure 6, we illustrate the detection performance of the rate constraint criterion as a function of the target concentration for two signal-to-noise ratios and average velocities. The maximum velocity was set at 3m/s, the sonar resolution at 10cm and the time required to manoeuver around an obstacle at 5s. For an average velocity of 0.5m/s as compared with 2.5ms, we have a relatively large margin between the maximum velocity and the average, and therefore more time can be spent in manoeuvring. Hence, the vehicle can successfully navigate a denser target field as indicated by the breakpoint in the detection probability curve being farther to the right. The breakpoint is located where the target concentration $\pi$ equals the threshold crossing rate *r*. For example, with $v_a = 0.5$m/s the rate is 0.033 which is the concentration at which the performance drops off.

For the lower signal-to-noise ratio the detection probability is lower, as expected. These detection curves approach those of the higher signal-to-noise ratio as the concentration increases and both curves tend to *pd=r*.

Figure 7 compares the high signal-to-noise ratio performance of the rate constraint criterion with that of the Neyman-Pearson criterion. Curves for three probabilities of false alarm are shown. It is evident that none of these curves is higher than that for the rate constraint criterion. Before the breakpoint the Neyman-Pearson curves will increase with decreasing *pf* if $r_{NP} > r$ but otherwise will decrease as shown in the figure. After the breakpoint, low *pf*'s allow the Neyman-Pearson

performance to approach the rate constraint performance but never surpass it.

It is possible, in theory, to find a *pf* that allows the Neyman-Pearson criterion performance to approach that of the rate constraint criterion. However setting this in practice is very difficult because we don't have knowledge of the probability distributions or the target concentration. Neither is required for the rate constraint criterion.

These figures illustrate the expected performance and optimality of the rate constraint criterion over a wide range of target concentrations. Two points are of significance here. The first is that even though we don't know the operating point in the sense of where it is on the performance curve we can still set it simply by adjusting the threshold to obtain the desired average velocity $v_a$. Once we have done this we are assured that the probability of mission success is a maximum even though we don't know what that maximum is.

The second point is that the rate constraint criterion, or more generally a resource constrained criterion, gives us a method by which we can relate our detection criterion to the goals of the organism or vehicle. This means that the statistical sensor can be integrated more intimately into the command and control structure of the vehicle.

## Concluding Discussion

Resource constraint tests implicitly imply a resource that must be managed and an objective for the detection system. For the radar/gun example in the introduction the resource was the gun firing rate and the objective was to protect the ship. For the obstacle avoidance sonar the resource was the permissible avoidance time and the objective was to avoid obstacles. In designing a detection system the question of application or objective must be addressed first. Why do we want this system, what is it supposed to do, and how much am I willing to spend to get it done? Again in the sonar example, somebody decided that a certain maximum avoidance time was all that was necessary or all they were willing to wait to protect the vehicle. A higher maximum speed would have helped as this would have increase the velocity margin and therefore raised *r*.

The essence of resource constrained detection is that the sonar is viewed as a device that identifies the k most likely cells to contain targets whether there are targets present or not. It is up to the rest of the system to decide what to do with those cells. For example, coincidence of cells in adjacent lists could be used to build significance. This view of a sonar radically effects its design. Throughput and the building of coincidence become the design parameters of interest and probability distributions and thresholding become secondary concerns. This is not to say that optimum tests, nonparametric techniques, and normalization for noise and clutter are not important because they are. The better the test the better the resource constraint procedure is going to work.

Constraints on the detection system come from the environment as well as the resource and this must be recognized. Examples are: the time constant of target evolution and the nature of the support for coincidence. Targets are detectable for a finite period of time after which they may be lost or a new detection sequence required to detect them. If the sonar does not process cells within this time period performance drops.

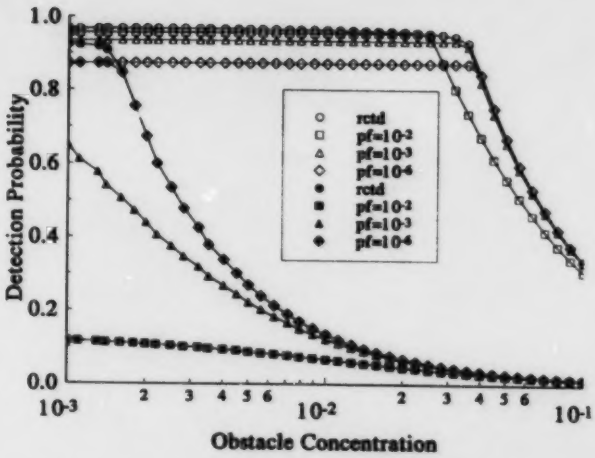



***Figure 7. High snr comparison between rate constaint and Neyman-Pearson criterion. The filled symbols correspond to $v_a$=2.5m/s, the hollow symbols to $v_a$=0.5m/s.***

Support for coincidence generally comes from two sources: time or space. Coincidence over time is employed to support the presence of a target when the target is of small extent when compared to a test cell. For extended targets such as those that would be the object of an obstacle avoidance sonar, coincidence could be required over space (across cells). In either case resources are consumed to establish the coincidence. These might well be the constraining resources on the system.

Resource constraint detection is a means by which the detection process can be controlled in practical applications because it reflects the real objectives of the system and the constraints placed upon it. This provides a mechanism by which the detection system can be integrated into a hierarchal command and control system. In fact, the process of selectively eliminating cells from further processing can be viewed as information filtering whereby only that information which is important for the mission is passed to the next level. Our future work will focus on the practical implications and a theoretical description of this information flow process.

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# Cryogenic D.C. and Low Frequency Noise Characteristics of Resonant Tunnelling Diodes

Anthony Ng

*Low frequency noise spectra and d.c. characteristics of AlAs/GaAs/AlAs resonant tunnelling diodes were measured at different temperatures between 77K and 300K. From the d.c. characteristics, it was found that the valley current $I_v$ follows an Arrhenius-type of temperature-dependent behavior of the form $I_v \sim I_{v0} \exp(-E_A/kT)$. The activation energy $E_A$ was found to be ~120meV in the high temperature regime (>350K) and a saturation of $\ln(I_v)$ in the low temperature regime (down to 77K) indicates that more than one process is involved in the excess valley current generation. The low frequency noise spectra had an $f^{-\alpha}$ dependence with a between 0.8 to 1.2 over the temperature range of 77K to 295K. The low frequency noise spectra were also modelled into discrete Lorentzian components from which the trapping times and a corresponding activation energy of ~150meV were determined. This activation energy is in close agreement with that determined from the Arrhenius-type relationship of the valley current. Detailed measurements of the voltage-bias temperature dependent noise spectra, as well as variation of other d.c. parameters such as the peak and valley currents and the peak and valley voltages are also included in this study.*

## Introduction

Resonant tunneling diodes continue to be the subject of intense research investigations because of their interesting physics and their potential for high speed and wideband electronic, optical and opto-electronic applications [1-5]. These devices have already been used as microwave and millimeter wave oscillators, and preliminary digital circuits have been proposed. In addition, potential applications as mixers, negative resistance amplifiers, and photodetectors are currently under intense investigation. However, there has been much less effort devoted to studying the low frequency noise characteristics of these devices at varying low temperatures, and to correlating the noise spectra to their d.c. characteristics.

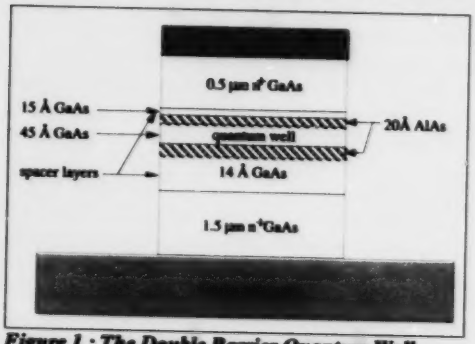



***Figure 1 : The Double Barrier Quantum Well Device consists of a layer of undoped barrier layers of AlAs (20Å) sandwiching the undoped 45Å GaAs well layer.***

The intention of this paper is to describe in detail the d.c. and low frequency noise spectral density measurements at varying temperatures and biasing voltages, and to correlate these measurements in an attempt to elucidate the noise characteristics of these resonant tunneling diodes. In addition, we expect that these comparisons will indicate inhomogeneities such as trapping centres and activation processes in the quantum well heterostructures.

## Background and Experimental Details

The diodes investigated here are double barrier heterostructures which consist of a layer of undoped GaAs sandwiched between two barrier layers of AlAs as shown in figure 1. To briefly review the operation of the double barrier resonant tunnelling diode (RTD), we show in figure 2 the energy band diagram in which $E_0$ is the energy of the first quasi-bound state in the

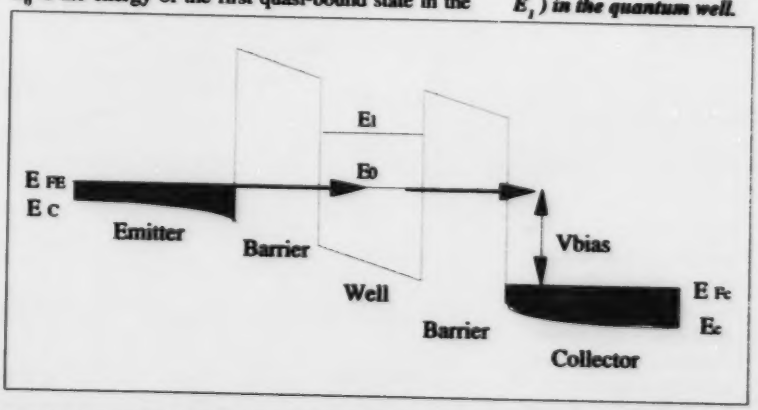



***Figure 2 : Excess current reaches a maximum when the Fermi energy of the emitter matches the quasi-bound state energy $E_0$ (or $E_1$) in the quantum well.***

Reprinted from the 1991 CSS Graduate Student Review. Mr. Ng is an M.A.Sc. student in the Faculty of Engineering Science.

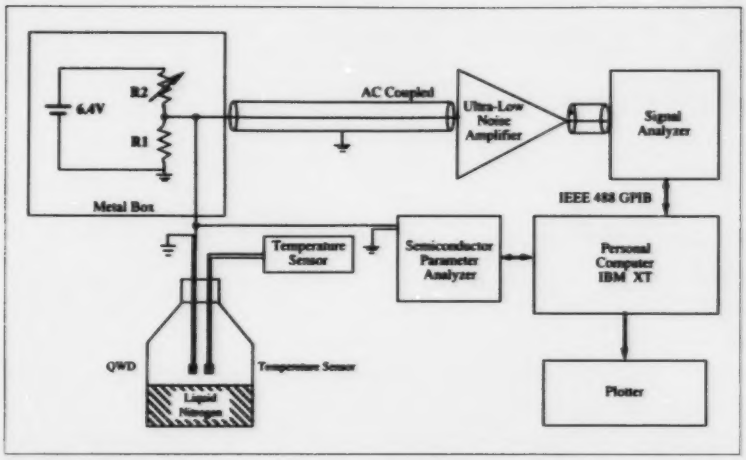



***Figure 3 : Block diagram of the d.c. and low frequency noise measurement system. Special care was taken to minimize noise and shielded cables were used.***

quantum well. When a voltage bias is applied to the RTD, the Fermi levels are shifted, and if the bias is such that the emitter Fermi level lines up with the quasi-bound energy $E_0$, then carriers can tunnel resonantly through the double barrier structure [6]. The current through the device increases to a peak value ($I_p$) when $E_0$ lines up with the emitter conduction band energy ($E_c$) and then decreases thereafter on further increase in applied bias to a minimum value ($I_v$). Further increases in applied biases results in an increase in the current. Thus, in a RTD, there exists a negative differential resistance region (NDR) between $I_p$ and $I_v$ and it is this NDR which makes the RTD such an important device for a variety of electronic and optical applications. [6-10]

In quantum well devices (QWD), it has been shown [7] that tunnelling can also occur through trap levels located near the emitter-barrier heterojunction. In this case, the carriers can tunnel through the trap level to $E_0$ even when the bias conditions for maximum tunnelling have not been reached. Here, generation-recombination between a trap level and the emitter conduction band results in random noise currents [7] of the form

$$i(t) = A \exp(-t/\tau) \quad (1)$$

where A is a constant depending only on the trap density and its degeneracy. The spectral content of the random noise current is given by

$$i(\omega) = A\tau / (1 + j\omega\tau) \quad (2)$$

where $1/\tau = 1/\tau_e + 1/\tau_c$ is the composite time constant of the trap level, and $\tau_e$ and $\tau_c$ are the capture and emission time constants. Therefore the generation-recombination activity of trapping levels will have an identifiable Lorentzian shape [8-9]. In our noise measurements, we observed only one or two Lorentzian components in the noise spectrum at each biasing voltage. From the Lorentzian-shaped noise spectrum we can determine the corner frequency $f_c$ which is related to $\tau$ by $\tau = 1/(2\pi f_c)$. Then using the relationship of Hoffmann and Sohn [10],

$$1/\tau = \rho N_c \exp(-E_A/kT) \quad (3)$$

and

$$S_i = r/V_{th} = r/(3kT/m_e^*)^{1/2} \quad (4)$$

where

h = Plank's constant,
r = recombination coefficient for the capture of electrons,
$N_c$ = effective density of states in the conduction band,
k = Boltzmann's constant
$V_{th}$ = thermal velocity,
$m_e^*$ = effective mass of an electron

and substituting (4) into (3), we have

$$\ln(\tau T^2) = (E_A/k)(1/T) - \ln(BS_i) \quad (5)$$

where $B = k^2 m_e^* (96)^{1/2} h^{-3}$. Hence if we plot $\ln(t\,T^2)$ vs $(T^{-1})$, a straight line with a slope of $E_A/k$ and ordinate intersection -log $(BS_i)$ should be obtained.

The QWD's used were mounted in four-pin package and their d.c. and noise spectra were measured using the experimental set-up shown in figure 3. For the noise

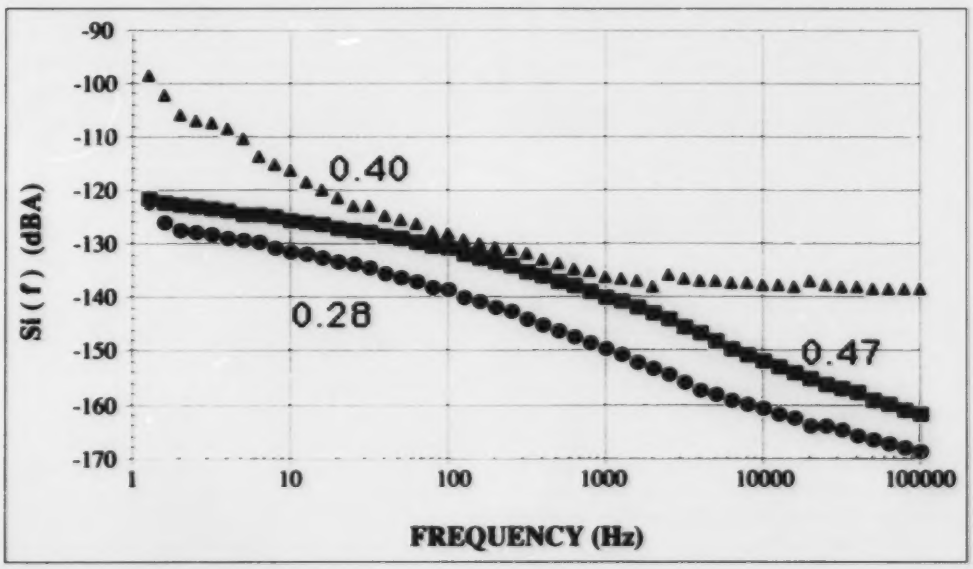



***Figure 4 : Noise current spectra at 184K and for three biasing voltages before, within, and after the negative differential resistance region. Note that $S_i(f)$ is largest for $V_b$= 0.4V (NDR biasing).***

measurements, low noise cabling was used and much attention was paid to minimize noise sources, and proper grounding and shielding of the system. Temperature measurements were made by varying the distance of the resonant tunnelling diodes above liquid nitrogen in a liquid nitrogen cryostat and measuring the voltage across a calibrated silicon diode temperature sensor. Care was taken to ensure that the temperature was stable for at least fifteen minutes before each measurement was made.

Noise spectra were measured for the system with the diode ($S_v(f)$) and without the diode ($S_v(f)_0$) in the circuit. From these measurements, the noise current spectral density of the resonant tunnel diode ($S_I(f)$) was determined [11] to be

$$S_I(f) = \frac{(R_1+R_2+R_D)^2\, S_V(f) - (R_1+R_2)^2 \cdot R_D^2 \cdot S_V(f)_0}{(R_1 \cdot R_2 \cdot R_D)^2} \quad (6)$$

In this equation, $R_1$ and $R_2$ are the biasing resistors, and $R_D$ is the dynamic resistance of the resonant tunnel diode at the biasing voltage.

## Results and Discussion

At each temperature between 300K and 77K, noise spectra were measured at three biasing voltages: before, within and beyond the NDR region of the diode. A typical example of the current noise spectra determined using equation (6) is shown in figure 4. Here, we see that $S_I(f)$ is highest within the NDR region, verifying the observation that the conduction of current through traps is a 'noisy' process, clearly distinguishable from low bias resonant tunnelling or conduction at biasing beyond the NDR region. The normalized current noise spectra $S_I(f)/I^2$ also showed the same bias and temperature dependence as $S_I(f)$, and outside the NDR region, both $S_I(f)$ and $S_I(f)/I^2$ decreased with increasing dynamic resistance $R_D$.

As explained in section 2, $S_I(f)$ can be modelled as a product of Lorentzian components [12], from which characteristic time constants could be extracted. Based on this, the corner frequencies ($f_C = 1/\tau$) were extracted from each noise spectra using the Levenberg-Marquardt (LM) algorithm [12]. Figure 5 shows an example of a corner frequency at five temperatures in which $f_C$ increases with temperature. In figure 5, the noise spectra between 5 Hz and 200 Hz was also modelled as flicker noise of the form $f^{-a}$. For $S_I(f)$ at temperatures between 77K and 300K, a was found to vary between 0.8 and 1.2. No conclusive dependence on either temperature or biasing voltages could be made from the $S_I(f)$ or the $S_I(f)/I^2$ spectra. However, we did observe that a was closest to 1 for biasing voltages in the NDR region.

From the extracted $f_C$ at various temperatures, Arrhenius-type plots of $\tau T^2$ versus $1000T^{-1}$ were made and the activation energies were determined from the slopes of such plots. An example of such plot is shown in figure 6. For our devices, $E_A$ was calculated to be 150 meV.

Measurements of the noise spectra $S_I(f)$ as a function of temperature and at fixed frequencies of 10, 100 and 1000Hz are shown in figure 7. These measurements indicate that $S_I(f)$ is not a monotonic decreasing or increasing function of decreasing temperature. Rather, it initially increases as the temperature decreases, but decreases thereafter on further decrease of temperature. Similar results were obtained by plotting the current normalized noise spectral density $S_I(f)/I^2$ versus temperature. These measurements also indicate that both $S_I(f)$ and $S_I(f)/I^2$ within the NDR region are higher than those outside the region at temperatures between 77K and 300K.

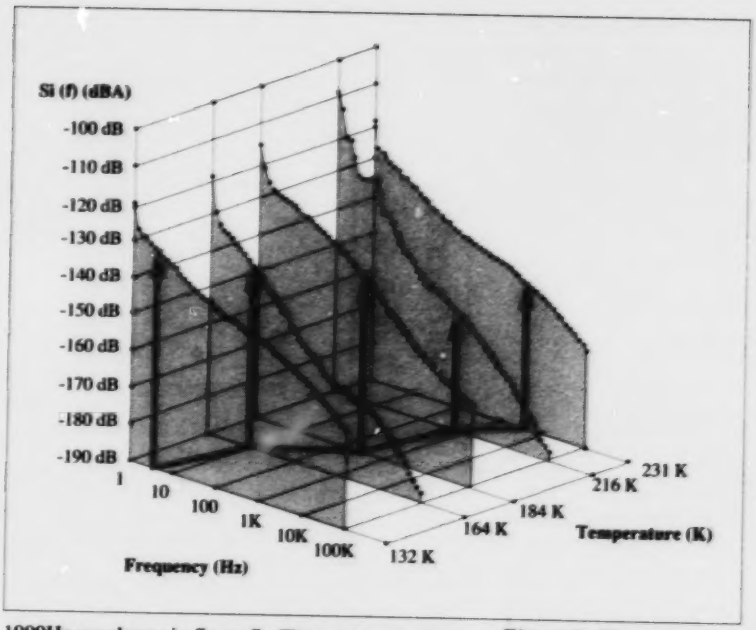



*Figure 5 : The corner frequencies measured at five different temperatures between 77K and 300K for one trap level are indicated with arrows. The corner frequency for this trap level increases with temperature.*

The d.c. measurements were also analyzed, and the peak $I_p$ and valley $I_v$ currents and peak $V_p$ and valley $V_v$ voltages were determined from the experimental current-voltage curves. The dependence of the I-V characteristic on the temperature is shown in figure 8. Here, we see that as the temperature decreases, both $I_v$ and $V_p$ decrease, but $I_p$ and $V_v$ increase. This is expected since decreasing temperatures result in reduced excess currents from thermionic emission, resulting in a reduced $I_v$. The increase in $I_p$ is due to the relative increase in the product of the Fermi supply function and the

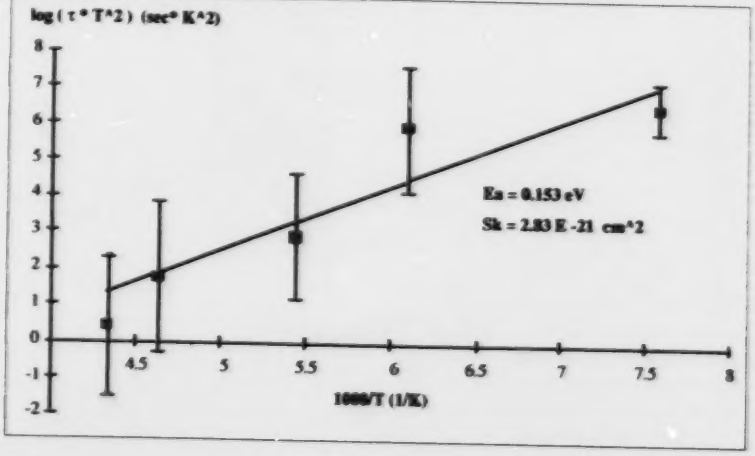



*Figure 6 : Arrhenius-type plot of $\tau T^2$ versus inverse temperature $1000T^{-1}$. The slope of this graph gives the activation energy of ~150meV for the forward biased diode.*

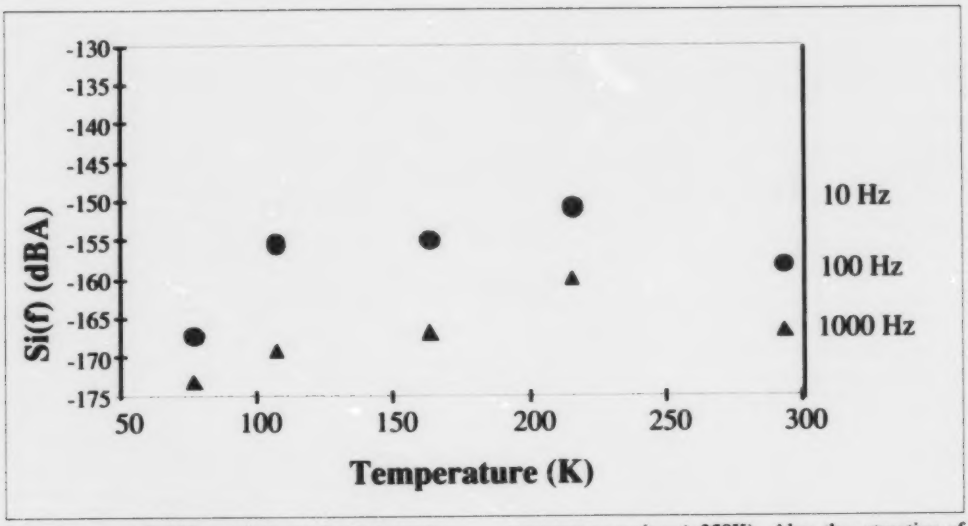



***Figure 7 : Noise spectra variation with temperature at the fixed frequencies of 10, 100 and 1000Hz and at the bias voltage of 0.28V.***

transmission probability with decreasing temperature. In addition, we note that the low voltage current levels are greatly reduced at the lower temperatures due to the reduction in the non-resonant contributions to the total device current. At high biases beyond the NDR region, there is a similar decrease in current with temperature since this current is predominantly thermionic in origin.

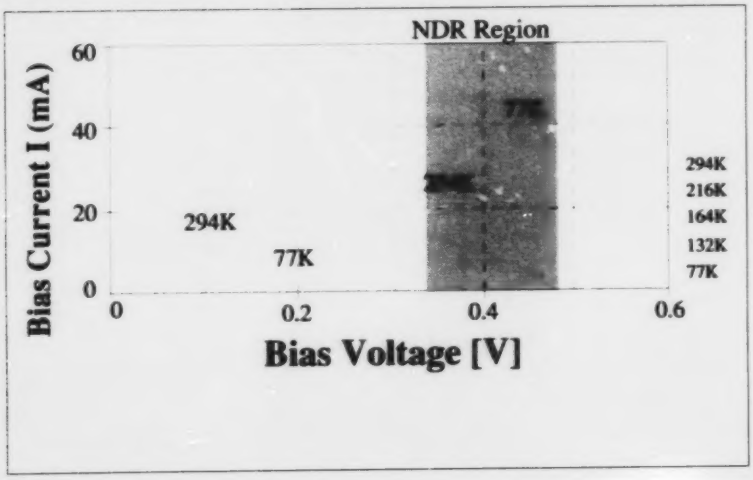
To illustrate the variations in $I_p$, $I_v$ and $I_p/I_v$ with temperature, figure 9 is drawn. From the above discussion, we expect an increase in $I_p/I_v$ with decreasing temperature. This increase is important for high peak-to-valley current ratio ($I_p/I_v$) which are essential to improved performance in quantum well-based circuits. For example, larger $I_p/I_v$ values would result in higher oscillation frequency and higher output power from quantum well oscillators.

From the plot of $I_v$ versus temperature, an Arrhenius-type of dependence on temperature [6] of the form

$$I_v \sim I_{v0} \exp(-E_A/kT)$$

is suggested. Therefore, $\ln(I_v)$ was plotted as a function of $1000 \cdot T^{-1}$, as shown in figure 10. From this figure, an activation energy of ~120meV was found for the high temperature regime (>350K). Also, the saturation of $\ln(I_v)$ at the lower temperatures down to 77K indicated that more than one process is involved in excess current generation. The activation energy determined from this Arrhenius plot is similar to that obtained from the plot of $\tau \cdot T^2$ versus $1000 \cdot T^{-1}$ described above. The small difference between the two results for the activation energy could be due to the uncertainty in determining the corner frequencies.

***Figure 8 : Dependence of the I-V characteristic on the temperature between 77K and 294K. The NDR region is shaded in this figure.***




## Conclusion

We have measured the low temperature d.c. characteristics and low frequency noise spectra of AlAs/GaAs/AlAs resonant tunnelling diodes. From the d.c. characteristics, it was found that the valley current followed an Arrhenius type of temperature-dependent behavior of the form $I_v \sim I_{v0} \exp(-E_A/kT)$. The activation energy $E_A$ was found to be ~120meV in the high temperature regime (>350K) and a saturation of $\ln(I_v)$ in the low temperature regime (down to 77K) indicated that more than one process is involved in the excess valley current generation. The low frequency noise spectra had a $f^{\alpha}$ dependence with a between 0.8 and 1.2 over the temperature range of 77K to 295K and for frequencies between 5 Hz and 200 Hz. The low frequency noise spectra were also modelled into discrete Lorentzian components from which the trapping times and a corresponding activation energy of ~150meV were determined to be in close agreement with those determined from the Arrhenius-type relationship.


## Acknowledgements

I would like to thank Dr. Jamal Deen, the head of the device physics group at Simon Fraser University, for supervising my work and for his numerous suggestions. His assistance and guidance during the preparation of this research are greatly appreciated. I would also like to thank Xiao Ming Li of the device physics group for his useful input.

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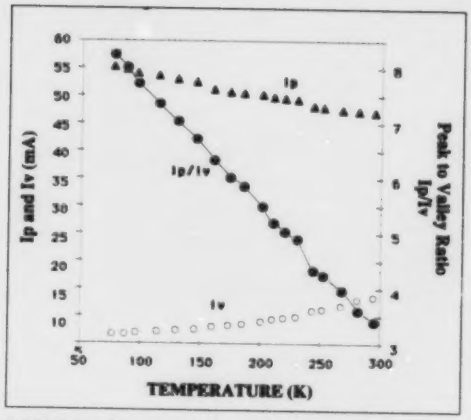


***Figure 9 : Variation of $I_p$, $I_v$ and $I_p/I_v$ with temperature. Note the large increase in $I_p/I_v$ with decreasing temperature due mainly to the decrease in $I_v$.***


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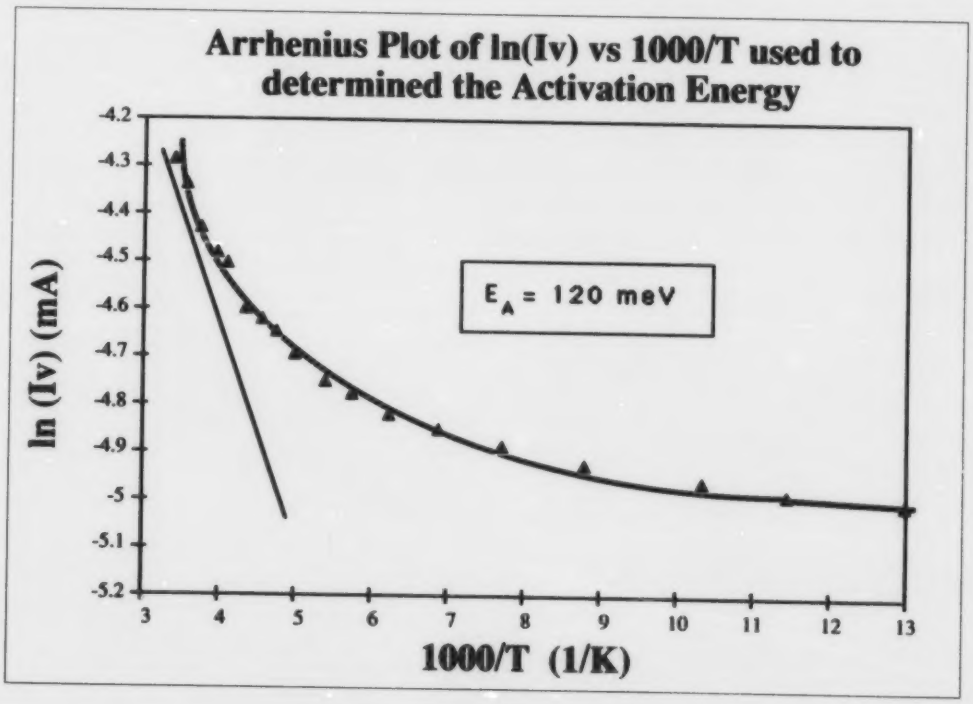
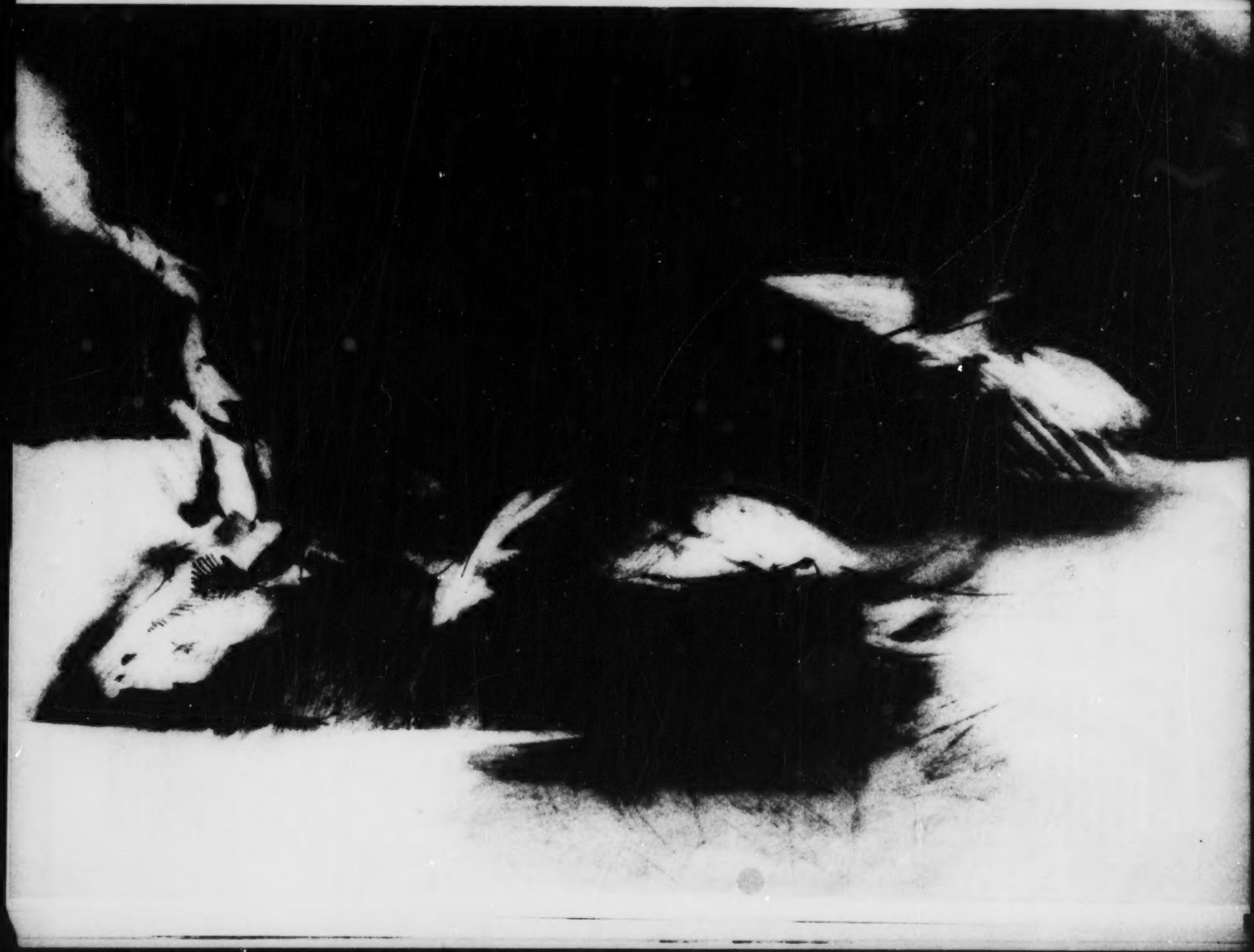



***Figure 10 : $\ln(I_v)$ was plotted as a function of $1000T^{-1}$. The activation energy above 350K was ~120meV. This Arrhenius type plot also suggest that more than one activation process is involved in the generation of $\ln(I_v)$.***



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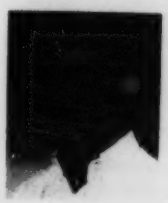

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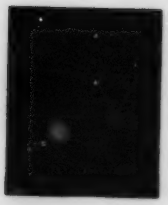

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291-4335

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291-3141

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291-3574

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Structural and electronic properties of intercalation systems and new materials called "inclusion solids" where monolayers of atoms are included between the layers of host materials; properties of monomolecular layers and interfaces; new materials for semiconductor gas sensors.

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291-3118

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Dipl. '76 Zhengzhou U.
M.S. '81 U. of Wisc.-Madison
Ph.D. '85 U. of Wisc.-Madison

Deductive database systems, knowledge-base systems, query compilation and processing, logic programming, knowledge discovery in databases, foundation of object-oriented databases, engineering and spatial databases.

291-4411

## Steve Hardy
### Professor, Engineering Science

B.Sc. '66 U. of Alberta
Ph.D. '71 U. of Alberta

Research interests encompass local area and packet radio network performance evaluation, high-speed communication circuits and devices, microelectronics and low temperature electronics and opto-electronics. 291-4332

## Ronald Harrop
### Professor, Mathematics
### Professor, Comp. Science

B.A. '46 Cambridge
M.A. '50 Cambridge
Ph.D. '53 Cambridge

Design and use of PET scanner for positron volume imaging; member of TRIUMF; use of PET in Alzheimer's research; SQUID technology in biomagnetic imaging of the brain. 291-4235

## Bill Havens
### Director, Expert Systems Lab

B.Sc. '69 Virginia Polytechnic
M.Sc. '73 Virginia Polytechnic
Ph.D. '78 U.B.C.

Constraint based hypothetical reasoning for expert systems; in particular constraint logic programming systems, intelligent backtracking, structural knowledge representation. 291-4973

## Katherine Heinrich
### Professor, Mathematics and Statistics

B.Math. '76 U. of Newcastle
Ph.D. '79 U. of Newcastle, Australia

Combinatorial designs; graph factorization and the interplay between graphs and designs; multipartite graphs; latin squares with orthogonality and subsquare properties. 291-3378

## Bretislav Heinrich
### Director, Surface Physics Lab

M.Sc. '62 Charles U., Prague
Ph.D. '67 Physics Institute, Prague

Optical properties of high temperature superconductors as studied primarily by light scattering experiments; the mechanism of superconductivity; optimization of the superconducting properties important in device performance. 291-4402

## Pavol Hell
### Professor, Computing Science

M.Sc. '69 McMaster U.
Ph.D. '72 U. of Montreal

Analysis of algorithms, complexity, graph theory, combinatorial optimization, especially relating to sorting, matching, colouring, independence and domination; linear programming duality and graph theory, combinatorics; algorithms for discrete optimization problems. 291-3391

## Paul Ho
### Assistant Professor, Engineering Science

B.Sc. '81 U. of Saskatchewan
Ph.D. '85 Queen's University

Advanced signalling, error control, and multiple access techniques and their application in mobile communications systems; modem techniques for mobile radio channels; signal design for MSAT. 291-3822

## Rick Hobson
### Associate Professor, Computing Science

B.Sc. '67 U.B.C.
Ph.D. '72 U. of Waterloo

VLSI system design, language directed computer architectures, parallel architectures, application specific integrated circuit design; prototype structured architecture machine incorporating new ideas in language interpretation and array processing. 291-4454

## Steven Holdcroft
### Assistant Professor, Chemistry

B.Sc. '83 U. of Salford, U.K.
Ph.D. '87 S.F.U.

Design, synthesis and application of electronically conducting polymers; photochemistry and photolithography of polymers; novel polymers for microelectronic applications. 291-4221

## Diane Ingraham
### Associate Professor, Engineering Science

B.Sc. '74 Dalhousie U.
S.M. '76 M.I.T.
Ph.D. '80 U.B.C.

Operation and training of neural nets; machine learning of music through MIDI keyboard; character, speech and pattern recognition; integrating production data with management information systems; integrated mill management. 291-4339

## Chuck Irwin
### Associate Professor, Engineering Science

BA..Sc. '58 U.B.C.
Ph.D. '65 U.B.C.

Optical properties of high temperature superconductors as studied primarily by light scattering experiments; optical properties and the mechanism of superconductivity and the optimization of superconducting properties which are important in device performance. 291-3160

## Ray Jennings
### Professor, Philosophy

B.A. '62 Queen's University
M.A. '65 Queen's University
Ph.D. '67 U. of London

Weak modal logics; the control of inference of inconsistent data, preference structures and conditional logic; development of the expent system language GALEN for medical diagnosis. 291-3329

## John Jones
### Associate Professor, Engineering Science

B.Sc. '74 U. of Sussex
Ph.D. '83 U. of Reading

Investigating the theory of design, with a view to developing a more intelligent computer aided design system; design for manufacture, and integration of finite-element analysis in the design process. 291-4679

## Tiko Kameda
### Professor, Computing Science
### Director, LCCR

B.S. '61 Tokyo U.
M.S. '63 Tokyo U.
Ph.D. '68 Princeton U.

Interested in concurrency control for database systems, distributed database systems, distributed computing, random testing of VLSI circuits, and algorithms for computer applications. 291-3307

## George Kirczenow
### Professor, Physics

B.Sc. '70 U. of W. Australia
D.Phil. '74 Oxford

Electronic transport theory in semiconductor nanostructures; quantum dots and quantum wires with characteristic dimensions < 100nm; quantum effects; miniaturization of microelectronic components. 291-3502

## Ramesh Krishnamurti
### Assistant Professor, Computing Science

B.Tech. '74 Indian Inst. Tech.
M.Tech '77 Indian Inst. Tech.
Ph.D. '87 U. of Pennsylvania

Approximation algorithms for combinatorial optimization problems, performance modelling, and parallel computing. 291-4116

## Alistair Lachlan
### Professor, Mathematics and Statistics

B.A. '59 Cambridge
M.A. '64 Cambridge
Ph.D. '64 Cambridge

Mathematical logic; properties of models of first-order theories which are tree-decomposable in the sense of Baldwin and Shelah; partial ordering of enumeration degrees in recursion theory. 291-3335

## Albert Leung
### Associate Professor, Engineering Science

B.S. '74 Case Western Reserve
M.S. '77 Case Western Reserve
Ph.D. '81 Case Western Reserve

Working on QuickChip, a facility for rapid prototyping application specific IC's in 24 hours using semi-custom wafers. Managing Intertech Systems Inc., a company that markets the technology. 291-4296

## William Leiss
### Vice President, Research Professor, Communications

BAA '60 F. Dickinson, N.J.
M.A. '63 Brandeis
Ph.D. '69 U.C. San Diego

Management of technology, public policy issues for research and development, and risk communication. 291-4152

## Ze-Nian Li
### Assistant Professor, Computing Science

B.S. '70 China U. Sci. & Tech
M.S. '81 U. Wisc.-Madison
Ph.D. '86 U. Wisc.-Madison

Parallel and hierarchical algorithms for computer vision in large multicomputer networks, active vision, sensing and object recognition for robotics and automation, knowledge representation and uncertainty management in intelligent systems. 291-3761

## Arthur L. Liestman
### Director, School of Computing Science

B.G.S. '75 U. of Kansas
M.S. '78 U. of Illinois
Ph.D. '81 U. of Illinois

Efficient and reliable methods for the dissemination of information in distributed computing environments; algorithms for distributed computing. 291-4197

## Wo-Shun Luk
### Associate Professor, Computing Science

B.A. '71 U. of London
M.S. '73 U. of Waterloo
Ph.D. '76 U. of Alberta

High-performance distributed database systems on local area networks with distributed sorting, join operations, transitive closure and concurrency control; spacial databases; object-oriented databases. 291-4619

## Christine MacKenzie
### Professor, Kinesiology

B.A. '75 U. of Waterloo
M.Sc. '78 U. of Waterloo
Ph.D. '81 U. of Waterloo

Kinetics of hand motions; planning and controlling movements such as gripping and grasping; computational models of manual tasks; 3D kinematics of talks like piano playing. 291-3573

## Paul McFetridge
### Assistant Professor, Linguistics

B.A. '80 S.F.U.
M.Sc. '81 S.F.U.
Ph.D. '89 S.F.U.

Director of the Natural Language Understanding group; computational linguistics concentrating on syntax and morphology of natural language and its application to information retrieval systems. 291-3239

## Ron Marteniuk
### Professor, Kinesiology

B.A. '63 U. of Alberta
M.A. '66 U. of Alberta
Ed.D. '68 U.C. Berkeley

Opto-electric 3D analysis of the kinetics of human movement to uncover the central nervous system mechanisms responsible for the learning and coordination of complex human movement skills. Potential applications in robotic design, ergonomics and rehabilitation.
291-3239

## Vito Modigliani
### Professor, Psychology

D.F. '60 U. of Rome
M.A. '68 Wayne State U.
Ph.D. '69 Wayne State U.

Psychology of memory and classification; in particular, the relationship between features, stimuli, and categories with an emphasis on top-down processes.
291-3744

## Roy Morrison
### Professor, Physics
### Director, Energy Research Institute

B.A. '48 U.B.C.
M.S. '49 U.B.C.
Ph.D. '53 U. of Pennsylvania

Semiconductor gas sensors based on various oxides; noise in semiconductors, particularly IF noise; reforming disulfide layer compounds into new composite structures. 291-3151

## Ash Parameswaran
### Assistant Professor, Engineering Science

B.Sc. '82 Madras U., India
M.Sc. '85 U. of Alberta
Ph.D. '90 U. of Alberta

Fabrication of integrated, micromachined silicon sensors and actuators; analysis of actuation mechanism; FEM analysis of microstructures; resonant structures for high resolution mass measurement and biomedical applications.
291-4971

## Shahram Payandeh
### Assistant Professor, Engineering Science

B.Sc. '81 U. of Akron, Ohio
M.Sc. '82 U. of Akron, Ohio
M.A.Sc. '86 U. of Toronto
Ph.D. '90 U. of Toronto

Robot mechanics and control, kinematics of mechanisms, grasping and manipulation, knowledge-based approaches in robotics. 291-4290

## Tom Perry
### Professor & Chairman, Linguistics

B.A. '67 Wabash College
M.A. '69 Indiana U.
M.A. '70 Indiana U.
Ph.D. '75 Indiana U.

Investigating phonological components of linguistic theories in models of speech production and perception that are computationally specifiable; timing control in speech processing and recognition. 291-3554

## Joseph Peters
### Associate Professor, Computing Science

B.Sc. '74 Waterloo
M.Sc. '76 U. of Toronto
Ph.D. '84 U. of Toronto

Interested in distributed algorithms, parallel computing, combinatorial optimization and approximation, computational geometry and matroid theory.
291-3780

## Slawomir Pilarski
### Assistant Professor, Computing Science

M.S. '81 Tech. U. Warsaw
Ph.D. '85 Inst. Elec. Tech. Warsaw

Interested in built-in self-test for VLSI circuit design; concurrent error detection; and distributed systems.
291-3774

## Tom K. Poiker
### Professor, Geography

Ph.D. '66 U. of Heidelberg

Interested in geographic information systems and computer cartography; also theoretical economic geography. Developed TIN (Triangulated Irregular Network) which is now being expanded to the treatment of terrain as networks.
291-4515

## Fred Popowich
### Assistant Professor, Computing Science

B.Sc. '82 U. of Alberta
M.Sc. '85 S.F.U.
Ph.D. '89 U. of Edinburgh

Computational linguistic frameworks describing structure and meaning with constraints instead of processes; natural language interfaces for intelligent systems; parsing, logic grammars, constraint logic programming, inheritance, and formal linguistics. 291-4193

## Andrew Rawicz
### Professor, Engineering Science

M.Sc. '73 U. of Krakow
Ph.D. '80 Tech. U. of Gliwice

Semiconductor retinas; nonlinear optics; reliability physics and engineering; also sensors, transducers and instrumentation. 291-3819

## William Richards
### Associate Professor, Communications

B.A. '71 Michigan State U.
M.A. '73 Stanford
Ph.D. '76 Stanford

Communication network analysis theory; the dynamics of communication/information networks; network analysis methods and tools.
291-4119

## Arthur Roberts
### Associate Professor, Geography

B.A. '71 U. of Toronto
M.A. '77 U. of Waterloo
Ph.D. '82 York University

Multispectral video and photographic airborne remote sensing of water quality; radiometric image correction based on colour vision theory; low cost microcomputer controlled remote sensing; Pleistocene geography of Canada.
291-3365

## Wyn Roberts
### Professor, Linguistics

B.A. '59 U. of Wales
B.A. '61 Cambridge
M.A. '68 Cambridge
Ph.D. '68 Cambridge

Development of quantal theory of phonetics-linguistics. Several major works in progress. 291-3678

## Robert Russell
### Professor, Mathematics and Computing Science

B.A. '67 U. of New Mexico
M.A. '68 U. of New Mexico
Ph.D. '71 U. of New Mexico

Dynamical systems—computation of invariant/inertial manifolds and computer graphics; partial differential equations—moving mesh methods and spectral methods; ordinary differential equations—bifurcation analysis and adaptive mesh techniques. 291-4819

## Mehrdad Saif
### Assistant Professor, Engineering Science

B.S.E.E. '82 Cleveland State U.
M.S.E.E. '84 Cleveland State U.
D.Eng.Sc. '87 Cleveland State U.

Systems and control theory. Particularly interested in the analysis and design of intelligent fault tolerant control systems, robust estimation/control, decentralized control of large scale systems, multivariable and optimal control theory. 291-3119

## Ross Saunders
### Professor, Linguistics

B.A. '61 Penn. State U.
A.M. '64 Brown University
Ph.D. '70 Brown University

Semantic and pragmatic domain of natural languages. 291-3924

## Tom Shermer
### Assistant Professor, Computing Science

B.E.S. '84 Johns Hopkins
Ph.D. '89 McGill University

Visibility and the computational aspects of the interplay between combinatorics and geometry; application areas include robotics, motion planning, and computer graphics.
291-3601

## Gerri Sinclair
### Director, EXCITE
### Faculty of Education

B.A. '68 U.B.C.
Ph.D. '76 U.B.C.

Interactive multimedia technologies in education; multimedia curriculum development; optical information systems and virtual reality systems for education; teacher education for the information-age classroom.
291-3615

## Shawn Stapleton
### Associate Professor, Engineering Science

B.Eng. '82 Carleton U.
M.Eng. '84 Carleton U.
Ph.D. '88 Carleton U.

High frequency devices and circuits; nonlinear phenomena of active microwave circuits; GaAs monolithic microwave integrated circuits; linearization of power amplifiers; and quantum wells.
291-4846

## Theodor Sterling
### Associate Professor, Computing Science

B.A. '49 U. of Chicago
M.A. '52 U. of Chicago
Ph.D. '55 Tulane University

Risk models; methods of using large existing data files to develop public policy; impact of information systems on political—especially democratic—processes. 291-4685

## Tim Swartz
### Assistant Professor, Statistics

B.Math. '82 U. of Waterloo
M.Sc. '83 U. of Toronto
Ph.D. '86 U. of Toronto

Regression analysis with errors having normal densities modified by positive polynomials; comparing sampling from product quadrature rules and the bootstrap method to assess statistical accuracy; and computational problems arising in Bayesian statistics.
291-4579

## Marek Syrzycki
### Associate Professor, Engineering Science

M.Sc. '70 Tech. U. of Warsaw
Ph.D. '78 Tech. U. of Warsaw

Semiconductor devices; analog and digital integrated circuits; semiconductor fabrication processes and silicon micromachining; integrated sensors and transducers; smart vision sensors; sensor fusion; novel devices and circuits for ASICs; large transducer arrays; built in redundancy.
291-3659

## Mike Thewalt
### Professor, Physics

B.Sc. '72 McMaster U.
M.Sc. '75 U.B.C.
Ph.D. '77 U.B.C.

Cryogenic photoluminescence imaging for characterizing semiconductors like Si, Ge, and GaAs; quantitative impurity analysis in high purity semiconductors; transient photolumi-nescence and excitation spectra of III-V heterostructures; tunable lasers, ultra-sensitive visible Raman scattering and high resolution interferometer for IR absorption. 291-3384

## Peter Triantafillou
### Associate Professor, Computing Science

B.A. '86 York University
M.Sc. '87 U. of Western Ont.
Ph.D. '91 U. of Waterloo

Distributed computing systems; concurrency control algorithms for efficient recovery from data loss and other failures. 291-5823

## Jacques Vaisey
### Assistant Professor Engineering Science

B.Sc. '80 U. of Manitoba
M.Sc. '82 Queens U.
Ph.D. '89 U.C. Santa Barbara

Image compression, signal processing and digital communications; personal mobile video. 291-4528

## Harold Weinberg
### Professor, Psychology

B.Sc. '58 U. of Washington
M.Sc. '60 U. of Washington
Ph.D. '63 U. of Washington

Brain systems information processing; assessment of closed head injuries; cognitive retraining software; use of SQUID technology in biomedicine. 291-3355

## Larry Weldon
### Associate Professor Statistics

B.Sc. '65 U. of Toronto
M.Sc. '66 U. of Toronto
Ph.D. '69 Stanford University

Cross-sectional sampling methods, multivariate estimation, applied probability models, and quality control in industry. 291-3667

## Richard Wright
### Assistant Professor Psychology

B.S.Ed. '71 Bucknell University
M.S.Ed. '72 Bucknell University
Ph.D. '76 Stanford University

Intermediate mechanisms in visual perception; visual routines in the perception of spatial relations; visual tracking and dynamics; visual perception and cognition. 291-5881

## Manfred Trummer
### Associate Professor, Mathematics

M.Sc. '79 ETH Zurich
Ph.D. '83 ETH Zurich

Numerical analysis. In particular computational methods for differential equations and integral equations arising in a variety of applications. 291-3799

## William Wedley
### Professor Business Administration

B.Com. '63 U.B.C.
M.B.A. '64 Columbia U.
Ph.D. '71 Columbia U.

Computer applications in business; analytic hierarchy process and other decision analyses; expert systems. 291-4528

## James Weinkam
### Professor, Computing Science

B.S. '64 Xavier University
M.S. '67 U. ofChicago
D.Sc . '70 Washington U.

Computational methods for radiation therapy planning; analysing large public health data files. 291-4667

## Philip Winne
### Professor, Education
Associate Member, Psychology

B.S.Ed. '71 Bucknell University
M.S.Ed. '72 Bucknell University
Ph.D. '76 Stanford University

Knowledge representation about instruction; using AI applications to help teachers improve lesson planning and develop intelligent tutoring systems. 291-4858

# Visiting Scientists

Prof. Robert Bland (c/o Pavol Hell)
*Cornell University*
Ordered matroids and optimization

Tian Ming Chen (c/o Albert Leung)
*University of Ching Du, China*
Laser direct-write technology

Daniel Costa (c/o Pavol Hell)
*Ecole Polytechnique Federale Lausanne*
Genetic algorithms, tabu search, scheduling.

Eliseo Clementini (c/o Nick Cercone)
*University of L'Aquila, Italy*
Deductive databases

Xiaotie Deng (c/o Tiko Kameda)
*York University*
On-line algorithms, agreement protocols

Mark Ellingham (c/o Brian Alspach)
*Vanderbilt University*
Combinatorics

George Fey (c/o Jeff Dahn)
*National Central University, Taiwan*
Rechargeable batteries

Krzysztof Gaj (c/o Swavek Pilarski)
*Warsaw University of Technology*
Data encryption, fault simulation software

Prof. Allen Gersho (c/o Vladimir Cuperman)
*University of California at Santa Barbara*
Speech coding

Prof. Jerry Griggs (c/o Pavol Hell)
*University of South Carolina*
Combinatorics, graphs and ordered sets.

Peter Horak (c/o Katherine Heinrich)
*Bratislava, Czechoslovakia*
Combinatorics

Russell Impagliazzo (c/o Arvind Gupta)
*UC San Diego*
Computational complexity and combinatorics

Toshihide Ibaraki (c/o Tiko Kameda)
*Kyoto University*
Boolean theory of coteries

H. A. Jung (c/o Brian Alspach)
*Technical University of Berlin*
Cycle problems

V. Karasyuk (c/o Mike Thewalt)
*Inst. of Radioengineering and Electronics, Moscow*
High resolution photoluminescence spectroscopy

Naoki Kato (c/o Tiko Kameda)
*Kobe University of Commerce*
Data structures for geographical data

Michael Knorrenschild (c/o Manfred Trummer)
*ETH, Zurich, Switzerland*

Andrzej Krasniewski (c/o Swavek Pilarski)
*University of Rochester N.Y.*
Circular self-test path of embedded RAM

Klaus Kriegel & Frank Hoffmann (c/o Tom Shermer)
*Karl-Weierstrauss Institut fur Mathematik, Berlin.*
Visibility problems in orthogonal polygons

Yuriria Lanza (c/o Tom Calvert)
*University of Venezuela.*

Geoff McKeown (c/o Warren Burton)
*University of East Anglia*

Prof. A. Mukhopadhyay (c/o Binay Bhattacharya)
*Indian Institute of Technology, Kanpur, India.*

Hiroshi Nagamochi (c/o Tiko Kameda)
*Kyoto University*
Coterie availability, network connectivity

Jaroslav Nesetril (c/o Pavol Hell)
*Charles University, Prague*
Combinatorics and graph theory.

Y. Pokrovskii (c/o Mike Thewalt)
*Inst. of Radioengineering and Electronics, Moscow*
Far intrared photoluminescence

S. Reich (c/o Bob Russell)
*Tech. Univ. Dresden*
Applied mathematics and numerical analysis

Davi Rumel (c/o Ted Sterling)
*University of Sao Paulo*
Public health issues

Karen Seyffarth (c/o Pavol Hell)
*U. of Waterloo*
Large planar networks

David M. Sloan (c/o Manfred Trummer)
*U. of Strathclyde, Glasgow, Scotland*

Ivan Stoev (c/o Marek Syrzycki)
*Bulgarian Academy of Sciences*
Solid state chemical sensors

S. E. Ulloa (c/o George Kirczenow)
*Ohio University*
Semiconductor transport in nanostructures

E. Van Vleck (c/o Bob Russell)
*Georgia Institute of Technology*
Dynamical systems and numerical computation

Dominique Vellard (c/o Nick Cercone)
*University of Nantes*
Cognitive psychology

Dr. Lev Vodopyanov (c/o Chuck Irwin)
*Lebedev Inst. of Physics, Moscow*

Sylvia Wessel (c/o M. Parameswaran)
*Newtech Industries*
Chemical sensors

M.-Y. Xu (c/o Brian Alspach)
*Beijing University*
Algebraic graph theory

Masafumi Yamashita (c/o Tiko Kameda)
*Hiroshima University*
Distributed algorithms

Kangsheng Zeng (c/o Jiawei Han)
*Zhejiang University China.*
Logic programming and deductive databases

Xuding Zhu (c/o Pavol Hell)
*University of Calgary*
Graph homomorphisms and colourings.

### Previous Visiting Scientists

Doug Seely (c/o Nick Cercone)
*South Australia Institute of Technology*
Instructional intelligent computing

Don Horner (c/o Philip Winne)
*Eastern Washington University*
Computer assisted learning and cognitive science

Marlene Jones (c/o Philip Winne)
*Senior Researcher, Alberta Research Council*
Instructional intelligent systems

Charles Colbourn (c/o Nick Cercone)
*U. of Waterloo*
Combinatorics and Optimization

Mark Gawron (c/o Tom Perry, Linguistics)
*Center for Study of Language and Information*
Situation Semantics

Gena Hahn (c/o Pavol Hell)
*U. of Montreal*
Graph Applications and VLSI

Yannis G. Kollias (c/o Warren Burton)
*National Technical University of Athens*
Geographic information and database systems

Han-Xiong Lian (c/o Jamal Deen, Steve Hardy)
*Beijing Inst. of Post and Telecommunications*
Devices/networks and opto-electronics

Gordon McCalla (c/o Nick Cercone)
*U. of Saskatchewan*
Intelligent systems

Victor Rayward-Smith (c/o Warren Burton)
*U. of East Anglia, England*
Functional programming

Zhixin Yan (c/o Jamal Deen)
*Shanghai, China*
Small Geometry MOSFET

Weining Zhang (c/o Wo Shun Luk)
*Louisville, KY*
Knowledge Base Systems

Pascal Van Hentenryck (c/o Bill Havens)
*Bull S.A., France*
Constraint Logic Programming

# Administrative Staff

## Office

Gail Brow
*Secretary*

Sandra Johnson
*Secretary*

Carolyn Seely-Morrison
*Administrative Assistant*

Barry Shell
*Research Editor*

## Research Computer Network

Stephan Chan
*Development Manager*

Ken Huckell
*Systems Analyst*

Tim Lee
*Operations Manager*

Frank Manuel
*Technologist*

Jean Woolley
*Group Assistant*

Hon-Man Wong
*Manager*

## Computational Intelligence, an International Journal

Nick Cercone and Gordon McCalla
*Editors*

Michelle Hoyle
*Editorial Assistant*

# Research and Technical Staff

Len Ashdown
*Instrument Machinist*

Martin Billing
*Engineering Technician*

Lyn Bartram
*Graphics Lab*

Troy Brooks
*Graphics Lab*

Armin Bruderlin
*Graphics Lab*

Laurie Byblow
*Graphics Lab*

Diana Cukierman
*Expert Systems Lab*

John Ens
*Parallel Vision Lab*

Dan Fass
*Natural Language Research*

Chris Groeneboer
*Natural Language Research*

Gary Hall
*Natural Language Research*

Yuming Hu
*High Frequency Research*

Xiao-Jian Huang
*Programmer/Researcher*

Ed Hutchings
*Research Technician*

Brad Kelly
*Research Technician*

G. Koeman
*Instrument Machinist*

Piyush Kothary
*Research Technician*

Wei Lu
*Programmer/Researcher*

Chantal Lunardi
*Programmer/Researcher*

Ken McDonald
*Analyst*

Peter McDonald
*Expert Systems Lab*

Vern Moen
*Physics Technician*

Neena Moorjani
*Research Associate*

Russ Ovans
*Expert Systems Lab*

Pat Pattabhiraman
*Research Associate*

Daya Ramgaur
*Expert Systems*

Greg Sidebottom
*Expert Systems Lab*

Don Smith
*Research Technician*

Thecla Schiphorst
*Graphics Lab*

Malte von Ruden
*Research Associate*

Michael Weber
*Research Technician*

Tao Wei
*Engineering Research Associate*

Bruce Wiebe
*Compter Research Associate*

Chris Welman
*Graphics Lab*

Yin Lam Wong
*Expert Systems Lab*

Ju Wu
*Computer Research Associate*

Yang Xiang
*Expert Systems Lab*

Zhaohui Xie
*Research Technician*

Z. Xu
*Engineering Research Associate*

Yuan Yao
*Computer Research Associate*

Z. Yan
*Research Technician*

Wei Zhou
*Computing Research Associate*

Z. Zuo
*Research Technician*

Yu Zhu
*Programmer/Researcher*

# Graduate Students

M. Abdou (Ph.D., Chemistry, S. Holdcroft)

C. Alakija (M.Sc., Eng. Sci., S. Stapleton)

J. Ales (M.Sc., Math, B. Alspach),

E. Altendorf (Ph.D., Physics, C. Irwin)

M. Arroyo (M.Sc., Chemistry, S. Holdcroft)

D. Atlan (Ph.D., Physics, B. Heinrich)

Y. Audet (Ph.D., Eng. Sci., G. Chapman)

V. Balasubramanian (Ph.D., Eng. Sci., M. Parameswaran)

S. Banneheka (M.Sc., Math, T. Swartz)

B. Battacharya (Ph.D., Eng. Science, V. Cuperman)

M. Baudais (M.Sc., Physics, J. Dahn)

B. Bauslaugh (Ph.D., Comp. Sci., P. Hell)

H. Bawtree (M.Sc., Comp. Sci., S. Atkins)

P. Belleville (Ph.D., Comp. Sci., T. Shermer)

A. Bennett-Brown (M.Sc., Comp. Sci., R. Hadley)

D. Brake (M.Sc., Physics, M. Thewalt)

L. Brassard (Ph.D., Comp. Sci., B. Funt)

D. Bremner (M.Sc., Comp. Sci., T. Shermer)

R. Brewster (Ph.D., Comp. Sci., P. Hell)

A. Bruderlin (Ph.D., Comp. Sci., T. Calvert)

D. Butler, (Ph.D., Instruct. Psych., P. Winne)

B. Cai (M.Sc., Comp. Sci., T. Kameda)

G. Carlow (Ph.D., Physics, R. Frindt)

L. Carr (M.A.Sc., Eng. Sci., M. Syrzycki)

Z. Celinski (Ph.D., Physics, B. Heinrich)

C. Chan (Ph.D., Comp. Sci., N. Cercone)

T. Chan, (M.A.Sc, Eng. Sci., P. Ho)

J. Chapman (Ph.D., Comp. Sci., T. Calvert and J. Dill)

W. Chen (M.Sc., Math, T. Swartz)

X. Chen (M.Sc., Comp. Sci., N. Cercone)

F. Chin (M.Sc., Comp. Sci., Z. Li)

K. Chin (M.Sc., Comp. Sci., R. Hadley)

C. Chociolko (Ph.D., Communication, W. Leiss)

B. Chong (M.Eng., Eng. Sci., S. Stapleton)

K. Collins (Ph.D., Comp. Sci., P. Hell)

F. Costescu (M.Sc., Eng. Sci., S. Stapleton)

D. Cukierman (M.Sc., Comp. Sci., V. Dahl)

D. Denis (M.A.Sc., Eng. Sci., M. Saif)

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B. Wang (M.A.Sc., Eng. Sci., J. Deen and S. Hardy)

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Y. Zhu (M.A.Sc., Eng. Sci., J. Deen)

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LCCR TR91-06 J. Han and K. Zeng **Automatic Generation of Compiled Forms for Linear Recursions**

LCCR TR90-22 J. Han **Capture of Sufficient Bindings for Irregular Linear Recursions**

LCCR TR90-13 N. Katoh, T. Ibaraki and T. Kameda **Efficient Implementation of Cautious Schedulers**

LCCR TR90-09 T. Ibaraki and T. Kameda **Theory of Coteries**

LCCR TR90-06 J. Han **Compilation and Evaluation of Linear Mutual Recursions**

LCCR TR90-02 J. Han and Q. Wang **Efficient Evaluation of Functional Single Linear Recursions in Deductive Databases**

LCCR TR89-04 T. Ibaraki, S. Harashima, M. Takeda and T. Kameda **Distributed Database Concurrency Control by Cautious Schedulers**

*Distributed Systems*

LCCR TR91-10 T. Ibaraki, H. Nagamochi and T. Kameda **Optimal Coteries for Rings and Related Networks**

LCCR TR91-04 X. Deng and T. Kameda **Reaching Byzantine Agreement in Amortized**

LCCR TR90-19 E. Moser and T. Kameda **Bounds on the number of hidden units of Boltzmann Machines**

LCCR TR89-14 S. Pilarski and T. Kameda **Checkpointing for Distributed Databases: Starting from the Basics**

*Algorithms*

LCCR TR91-01 C.J. Colbourn and K. Heinrich **Conflict-Free Access to Parallel Memories**

LCCR TR90-12 J.-C. Bermond, P. Hell, and J.-J. Quisquater **Construction of Large Packet Networks**

LCCR TR90-11 P. Hell, J. Bang-Jensen and J. Huang **Local Tournaments and Proper Circular Arc Graphs**

LCCR TR90-01 J. Bang-Jensen, P. Hell and G. MacGillivray **On The Complexity of Colouring By Superdigraphs of Bipartite Graphs**

LCCR TR89-08 P. Hell **Universality of A-Mote Graphs**

*Programming Languages*

LCCR TR91-05 F.W. Burton and Robert D Cameron **Pattern Matching with Abstract Data Types**

LCCR TR90-04 F.W. Burton V.J. Rayward-Smith **Limitations of Process Management in Distributed Systems**

LCCR TR89-03 F.W. Burton **Indeterminate Behavior with Determinate Semantics in Parallel Programs**

*VLSI Hardware*

LCCR TR91-02 S. Pilarski and K. Wiebe **Counter-Based Compaction: An analysis for BIST**

LCCR TR90-20 S. Pilarski, T. Kameda and Andre Ivanov **Sequential Faults and Aliasing**

LCCR TR90-16 T. Kameda, S. Pilarski and A. Ivanov **Notes on Multiple Input Signature Analysis**

LCCR TR90-10 S. Pilarski, A. Kransniewski and T. Kameda **Estimations of Testing effectiveness for the Circular Self-Test Path Technique.**

*Communications*

LCCR TR91-15 J.K. Cavers **Adaptive Compensation For Imbalance and Offset Losses In Direct Conversion Transceivers**

LCCR TR90-08 J.K. Cavers and R.F. Marchetto **A New Coding Technique for Spectral Shaping of Data**

LCCR TR90-07 J.K. Cavers **Amplifier Linearization Using A Digital Predistorter with Fast Adaptation and Low Memory Requirements**

LCCR TR89-17 H. Li and J.K. Cavers **An Adaptive Filtering Technique For Pilot Aided Transmission Systems**

LCCR TR89-16 J.K. Cavers **An Analysis of Pilot Symbol Assisted Modulation for Rayleigh Fading Channels**

LCCR TR89-09 J.K. Cavers and Paul Ho **Analysis of the error Performance of Trellis-Coded Modulation In Rayleigh Fading Channels**

LCCR TR89-07 E. Lo and R.H.S. Hardy **Simulation of a Polling System for Token Passing Networks using GPSS**

LCCR TR89-06 J.K. Cavers **The Performance of Phase Locked TTIB with Symmetric Phase Detection**

*Computational Vision*

LCCR TR91-14 G.D. Finlayson, M.S. Drew and B.V. Funt **Spectral Sharpening: Sensor Transformations for Improved Color Constancy**

LCCR TR91-09 B.V. Funt and G.D. Finlayson **Color Constant Color Indexing**

LCCR TR91-08 B.V. Funt, M. Drew and M. Brockington **Recovering Shading from Color Images**

LCCR TR91-03 M.S. Drew and B.V. Funt **Color Space Analysis of Mutual Illumination**

LCCR TR90-21 M.S. Drew and B.V. Funt **Variational Approach to Mutual Illumination in Color Images**

LCCR TR89-02 J. Ho, M.S. Drew and B.V. Funt **Color Constancy from Mutual Reflection**

*Miscellaneous*

LCCR TR90-14 S. Pilarski and T. Kameda **Simple Estimation of the Convergence Rate of a Markov Chain**

*Intelligent Systems*

CSS-IS TR 89-01 Saif **On the Structure of the Matrix Riccati Equation and the Associated LQ**

CSS-IS TR 89-02 McGeer **Passive Bipedal Running**

CSS-IS TR 89-03 R. Hadley **The Many Uses of 'Belief' in AI**

CSS-IS TR 89-04 R. Hadley **An Intension-Based Model of Nested Epistemic Processes**

CSS-IS TR 89-05 Saif **Optimal Modal Control**

CSS-IS TR 89-07 Saif & Guan **A Novel Approach to the Design of Unknown Input Observe**

CSS-IS TR 89-08 F. Popowich **A Tree Unification Grammar-Based Natural Language Processor**

CSS-IS TR 89-09 Hamilton **Reduction Reconsidered: Further Investigation of a Mechanism for Searching for Regularity in Data**

CSS-IS TR 89-10 Saif & Guan **Decentralized Observers for Large Scale Systems**

CSS-IS TR90-01 F. Popowich, C. Vogel **Chart Parsing Head-Driven Phrase Structure Grammar**

CSS-IS TR90-02 K. Gupta, Yalpani **Motion Planning in Time Varying Environment with Velocity**

CSS-IS TR90-03 R. Hadley **Connectionism, Rule Following, and Symbolic Manipulation**

CSS-IS TR90-04 R. Hadley **Reasoning with Truth Ascriptions, Self-Reference and Embedded Sentences in First-Order Logic**

CSS-IS TR90-05 Z. Li, F. Tong **On Improving the Accuracy of Line Extraction in Hough Space**

CSS-IS TR90-06 Z. Li, F. Tong, R. Laughlin **Parallel Algorithms for Line Detection On a IxN Array Processor**

CSS-IS TR90-07 W. Havens, S.Sidebottom, M. Cuperman, R. Davison, S. Gaudet and G. Sidebottom **Echidna Constraint Reasoning System: Programming Specifications**

CSS-IS TR90-09 W. Havens, S. Sidebottom, G. Sidebottom, J. Jones, M. Cuperman and R. Davison **Echidna Constraint Reasoning System: Next Generation Expert System Technology**

CSS-IS TR90-10 P. Pattabhiraman and N. Cercone **Natural Language Generation Systems and Theories**

CSS-IS TR 91-02 R. Hadley **A Sense-Based, Process Model of Knowledge and Belief** (Revised CSS-IS TR89-04)

CSS-IS TR 91-03 Z.N. Li, B. Yao, and F. Tong **On Linear Generalized Hough Transform and Parallelization**

CSS-IS TR 91-04 Chris Groeneboer and Nick Cercone **A User Interface Architecture Based on a Constructivist Paradigm**

CSS-IS TR 91-05 G. Sidebottom **Implementing CLP(B) using the Connection Theorem Proving Method and a Reason Maintenance System**

CSS-IS TR 91-06 G. Sidebottom, and W. S Havens **Hierarchical Arc Consistency Applied to Numeric Constraint Processing in Logic Programming**

CSS-IS TR 91-07 W.S. Havens **Intelligent Backtracking in the Echidna CLP Reasoning System**

CSS-IS TR91-08 F. Popowich and C. Vogel **The HPSG-PL System**

CSS-IS TR91-09 John Ens **A Parallel Link Between an AIS-4000 and a Transputer Pyramid**

CSS-IS TR91-10 K. Gupta, X. M. Zhu **Extracting Polyhedral Models From A Range Image: A Hybrid Approach**

CSS-IS TR91-11 K. Gupta, Z. Guo **Motion Planning for Many Degrees of Freedom: Sequential Search With Backtracking**

CSS-IS TR91-12 D. Fass and N. Cercone **Research in Natural Language Processing at Simon Fraser University**

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| A Machine Called Sam | Hobson | microprocessor, VLSI, Structured Architecture, chip, interpreter | 1 | 3 | Apr-89 |
| ASI News | | Industry Affilliates | 1 | 7 | Oct-89 |
| ASI News | | industry joint funding | 1 | 2 | Mar-89 |
| ASI News | Hell, Pilarski, Popowich | role of CSS, fellowships, industry | 1 | 1 | Jan-89 |
| Balancing Acts | Russell | Math, Differential equations, chaos, analytical computer models | 3 | 2 | Mar-91 |
| Bilingual Computers are Coming | Dahl | Translation, CWARC, grammar, AI, Language | 1 | 5 | Jun-89 |
| Business Administration Prof Joins CSS | Wedley | Decision Analysis | 2 | 4 | May-90 |
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| Challenging a Mountain of Administration | Calvert | Profile | 2 | 8 | Sep-90 |
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| Computing and Common Sense | Jim Delgrande | Logic, reasoning, AI, Belief, Tweety bird | 1 | 5 | Jun-89 |
| Computing Our True Colours | Funt | Vision, AI, colour constancy | 2 | 8 | Sep-90 |
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| Confidence From Random Bits | Pilarski, Kameda | Built in Self test, Microchips, microcircuits | 3 | 7 | Oct-91 |
| CSS Goes Japanese | Cercone, Han, Jennings, Aleliunas | Japan, trip, conference | 3 | 4 | May-91 |
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| CSS Networking Who's Who | Atkins, Cavers, Chapman, Cuperman, Deen, George, Guild, Hardy, Kameda, Liestman, Luk, Peters, Poiker, Richards, Stapleton | network | 2 | 9 | Nov-90 |
| CSS Participates in Centres of Excellence | Cercone | IRIS, PRECARN | 1 | 9 | Dec-89 |
| CSS Strategic Initiative Grants Awarded | Funt, Havens, Li, Saif, Syrzycki, Thewalt | Funding | 2 | 6 | Jul-90 |
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| Dahl's Book Now in Japanese | Dahl | Natural Language Understanding | 2 | 8 | Sep-90 |
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| Exciting Connections | Gerri Sinclair | Education, multimedia, prototyping, virtual reality | 3 | 7 | Oct-91 |
| Fellow Excites Materials with Lasers | Thewalt | Physics, microelectronics, gallium arsenide, semiconductors, photoluminescence | 1 | 6 | Aug-89 |
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| Getting Control Intelligently | Dill, Havens, Dickinson | Intelligent Graphic interface, control systems, telephone | 3 | 5 | Jun-91 |
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| History Of The CSS Network | Cercone, Calvert, George, Kameda, Luk , Richards, Sterling | SPARCstation, network, LCCR | 2 | 9 | Nov-90 |
| How did you get it? I ftp'd it! | Jones | ftp, network, anonymous, file transfer | 2 | 9 | Nov-90 |

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| How to Succeed in Business at SFU | Cornford | Industry, Liaison | 1 | 9 | Dec-89 |
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| Let the Digits Do the Talking | Cuperman, Ho | DSP, Voice recognition, speech, communications, telephone | 1 | 8 | Nov-89 |
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| Member Cuts Hair, Wins Award | Shermer | Ambridge Prize | 2 | 8 | Sep-90 |
| Micromachining Course Attended | Syrzycki, Parameswaran | Sensors, Nova | 2 | 7 | Aug-90 |
| Network Bottleneck Busting | Hardy, Deen, Stapleton | Network, communications, microelectronics, LAN, electrooptics | 1 | 9 | Dec-89 |
| Network Manager | Wong | | 2 | 6 | Jul-90 |
| Network Map | | map, internet address, naming, backbone, terminators | 2 | 9 | Nov-90 |
| Network Security | Hon-Man Wong | Virus, Crackers, Password, UNIX | 2 | 9 | Nov-90 |
| Networking the Future | Cavers, Cuperman, Ho, Hardy, Liestman, Peters, Kolotyluk, Luk, Kameda, Atkins | agents, network file system, distributed, electronic slate, wrist-watch, personal cellular, DSP, Voice recognition, FDDI, high-speed | 2 | 9 | Nov-90 |
| Networks of Excellence | Cercone, Delgrande, Kameda, Cavers, Hobson | IRIS, TRIO, MicroNet, Centres of Excellence, Knowledge Based Systems, Robotics, VLSI | 2 | 9 | Nov-90 |
| New Company: Echidna | Havens | Expert systems | 3 | 8 | Dec-91 |
| New CSS Faculty Appointments | Shermer, Chapman | Computer graphics, microelectronics | 1 | 8 | Nov-89 |
| New Expert Systems Head | Havens | Expert systems, tektronics | 1 | 1 | Jan-89 |
| New Head of Engineering Science | Cavers | Director | 2 | 7 | Aug-90 |
| New Life Form Evolving | Calvert | Dance, graphics, software, technology transfer, commercialization | 3 | 3 | Apr-91 |
| New Member | Kirczenow | nanostructures | 2 | 5 | Jun-90 |
| New member | Mark Drew | computer vision, colour perception | 3 | 6 | Sep-91 |
| New member | Richard Wright | Psychology, intermediate vision, cognition | 3 | 7 | Oct-91 |
| New Physics Members | Colbow, Irwin | sensors, thin-film semiconductors, scanning tunnelling microscope, high temperature superconductors, raman microscopy, SQUID | 3 | 2 | Mar-91 |
| New Sun Workstations Arrive | Maynard, Cercone, Calvert, George | Workstations, industrial partnerships | 1 | 7 | Oct-89 |
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| Pavol's Problems | Hell | combinatorics, NP-hard, Discrete mathematics | 1 | 3 | Apr-89 |
| Personal Networks | Krbavac | interpersonal, finance, registrar | 2 | 9 | Nov-90 |
| Plastic Microchips | Steve Holdcroft, Chapman, Leung | microchips, chemistry, conducting polymers, electronics | 3 | 6 | Sep-91 |
| Prof's Dilemma: Publish or Patent | Havens, Funt, Cornford, Trask | Patents, commercialization, univentures, liaison office | 3 | 3 | Apr-91 |
| Put an Artist in Your System | Cercone, Calvert, | Music, synthesizers, art, Centre for Image and Sound Research | 3 | 6 | Sep-91 |
| QuickChip | Leung | Microchip, laser, custom ASIC, microelectronics | 1 | 3 | Apr-89 |
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| Recognizing Fast Talkers | Perry | Speech, Linguistics, | 2 | 4 | May-90 |
| Research Computer Network Support Group | Wong | Network | 2 | 1 | Feb-90 |
| Robot Mouse Prize | Rawicz | Robotics, Gold prize, students | 3 | 8 | Dec-91 |
| Robot to Walk on Water | McGeer, Gupta | Robotics, bipedal walking, vision | 1 | 2 | Mar-89 |
| Robotics and Manufacturing Symposium | Saif | CAD/CAM/CIM, neural nets, vision, AI | 2 | 7 | Aug-90 |
| Sensational Physics | Frindt | Microchip, Sensor, Materials Science | 2 | 1 | Feb-90 |
| Seven New Members | MacKenzie, Marteniuk, Payandeh, A. Gupta, Godwin, Triantafillou | Kinesiology, Robotics, Coop, complexity, concurrency control, networks | 3 | 8 | Dec-91 |
| SF Univentures Closes Deals | Leung, Calvert, Cameron | QuickChip, dance, CASE | 2 | 9 | Nov-90 |
| SFU Launches High Tech Companies | Cornford | commercialization, univentures | 3 | 3 | Apr-91 |
| SFU's Artificial Intelligence IQ | Cercone | AI, Belief, Vision, Cognitive | 2 | 3 | Apr-90 |
| Social Implications of Networks | Benston, Jones, Richards | network, email, smiley | 2 | 9 | Nov-90 |
| Software Productivity Centre | | CASE tools, documentation, software engineering | 3 | 5 | Jun-91 |
| Student Paper Competition Winners | | | 3 | 6 | Sep-91 |
| Sun Still Shining on CSS | | SPARCstation, partnership, industry | 2 | 9 | Nov-90 |

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| Sunrise at SFU | Cercone | Sun, SPARCstation 1, network, partnerships | 1 | 4 | May-89 |
| Taking Risks in A Technological Society | Leiss | Risk, technology, environment, communications, information Society | 1 | 7 | Oct-89 |
| The 64 Kilobit per Second Question | Cavers | communications Mobile, readio, DSP | 1 | 6 | Aug-89 |
| The Applied Science of Administration | George | Dean | 2 | 5 | Jun-90 |
| The Art of Graph Spanning | Liestman, Shermer | Computing, Graph theory, limericks | 3 | 1 | Feb-91 |
| The Day the Network Died | Hon-Man Wong | CSS Computer network, SunOS4.1, UNIX | 2 | 9 | Nov-90 |
| The Experienced Expert | Havens | Expert Systems, CAD, echidna, constraint based reasoning | 2 | 2 | Mar-90 |
| The Management of Technology | Guild, George | Champions of Innovation, Networking, CPROST, telecommunications | 3 | 1 | Feb-91 |
| The Model Teacher | McCalla | Granularity, AI, intelligent tutoring systems, Expert Systems | 1 | 7 | Oct-89 |
| The Pet Project | Atkins, Harrop | brain scan, tomography, computer imaging, alzheimer's | 1 | 1 | Jan-89 |
| The Philosophy of Car Repair | Jennings | Expert System, McCarney, Automotive, diagnostic, | 1 | 4 | May-89 |
| The Social Context of Artificial Intelligence | Sterling | AI, future, technology | 1 | 9 | Dec-89 |
| The SPIRIT of the Deep | Bird | communications, underwater, subsea, ROV, robotics | 1 | 6 | Aug-89 |
| The Trouble With Truncation | Trummer | Math, differential equations, numerical methods, eigenvalues | 3 | 2 | Mar-91 |
| Thewalt on NSERC Selection Committe | Thewalt | NSERC | 2 | 8 | Sep-90 |
| Thin Film Superconductors | Heinrich, Gygax, Weinberg,Deen, Parameswaran | Materials science, superconductivity, Josephson Junction, SQUID | 3 | 4 | May-91 |
| Three New Members Join CSS | Dahn, Holdcroft, McFetridge | physics, chemistry, linguistics | 2 | 9 | Nov-90 |
| Tools For Materials Science Research at SFU | | Surface Physics Lab | 3 | 4 | May-91 |
| Underwater Testbed Shown at ROV'90 | Bird | Subsea, Communications, URL | 2 | 6 | Jul-90 |
| UNIX Commands for Networkers | | UNIX, network, commands | 2 | 9 | Nov-90 |
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| Visiting Researchers at CSS | Fass, Gawron | Linguistics, | 1 | 2 | Mar-89 |
| Voices From the Fifteenth Dimension | Bhattacharya | Speech, Speaker identification, Computational Geometry | 2 | 2 | Mar-90 |
| Wafer Scale Integration | Chapman | VLSI, microchip | 2 | 7 | Aug-90 |
| We Connect The Dots | Li, Luk, Atkins | Vision, Parallel computing, robot control | 3 | 8 | Dec-91 |

# Conferences, Symposia and Seminars

SYMPOSIUM ON QUALITY AND RELIABILITY
*October 24-25, 1991*

SEMINAR ON ADVANCED MANAGEMENT TECHNOLOGY
*July 1991*

THIRD INTERNATIONAL SYMPOSIUM ON ROBOTICS AND MANUFACTURING
*July 18-20, 1990*

CANADIAN CONFERENCE ON VLSI '89
*Oct 22-24, 1989*

DISTINGUISHED ADVANCED RESEARCH AND TECHNOLOGY SEMINARS

*These talks are held weekly. Selected examples:*

CMOS Devices and Technology for VLSI
*Dr. J.Y. Chen, Boeing Electronics Company*

Fault Tolerant Control of Large Scale Dynamical Systems
*Prof. G. Vachtsevanos, Georgia Institute of Technology*

Fuels for the Future
*Dr. A. Momenthy, Boeing Airplane Commercial Co.*

Low-Rate High Quality Speech Coding
*Dr. A. Bishnu, AT&T, NJ.*

Physical Device Models for Microwave and Milimeter Wave CAD
*Dr. C. Snowden, Leeds University,UK.*

Recent Progress in Motion Planning at Stanford
*Prof. J.C. Latombe, Stanford University*

Fault Detection via Artificial Neural Networks
*Dr. D. Himmelblau, University of Texas at Austin*

Congestion Control in ATM
*Prof. J. Hayes, Concordia University*

# Scholarships, Fellowships and Awards

## CSS Graduate Student Scholarships

Christine Dykstra, *Computer imaging of medical brain scans.*

Christine Chan, *Inferential model for knowledge acquisition in expert systems.*

Winston Byblow, *Computer visual displays that optimize human motor control dynamics.*

Greg Sidebottom, *Constraint logic programming for expert systems.*

Ranadir Gupta, *Semantic data modelling of object oriented databases.*

## Expert Systems Graduate Student Scholarships

D. Mitchell
G. Sidebottom
M. Verma
H. Yao
J. Zhan
D. Gaur
D. Li
J. Low
T. Lu
E. Rozsa

## Academic Chairs

NSERC Industrial Research Chair in Physics
Ebco/Epic Chairs in Expert Systems (two)

## University Research Professorships

George Kirczenow

## Patents

James Cavers, *Amplifier Linearization*
Conrad Colbow, *Layered Compounds*
Vladimir Cuperman, *Speech Coding*
Brian Funt, *Vision Algorithms*
Robert Frindt, *Sensors and Catalysts*
Steve Hardy, *Local Area Networks*
Bill Havens, *Expert Systems*
Steve Holdcroft, *Electrically Conducting Polymers*
Albert Leung, *Microchip Fabrication*
Roy Morrison, *Sensors and Catalysts*

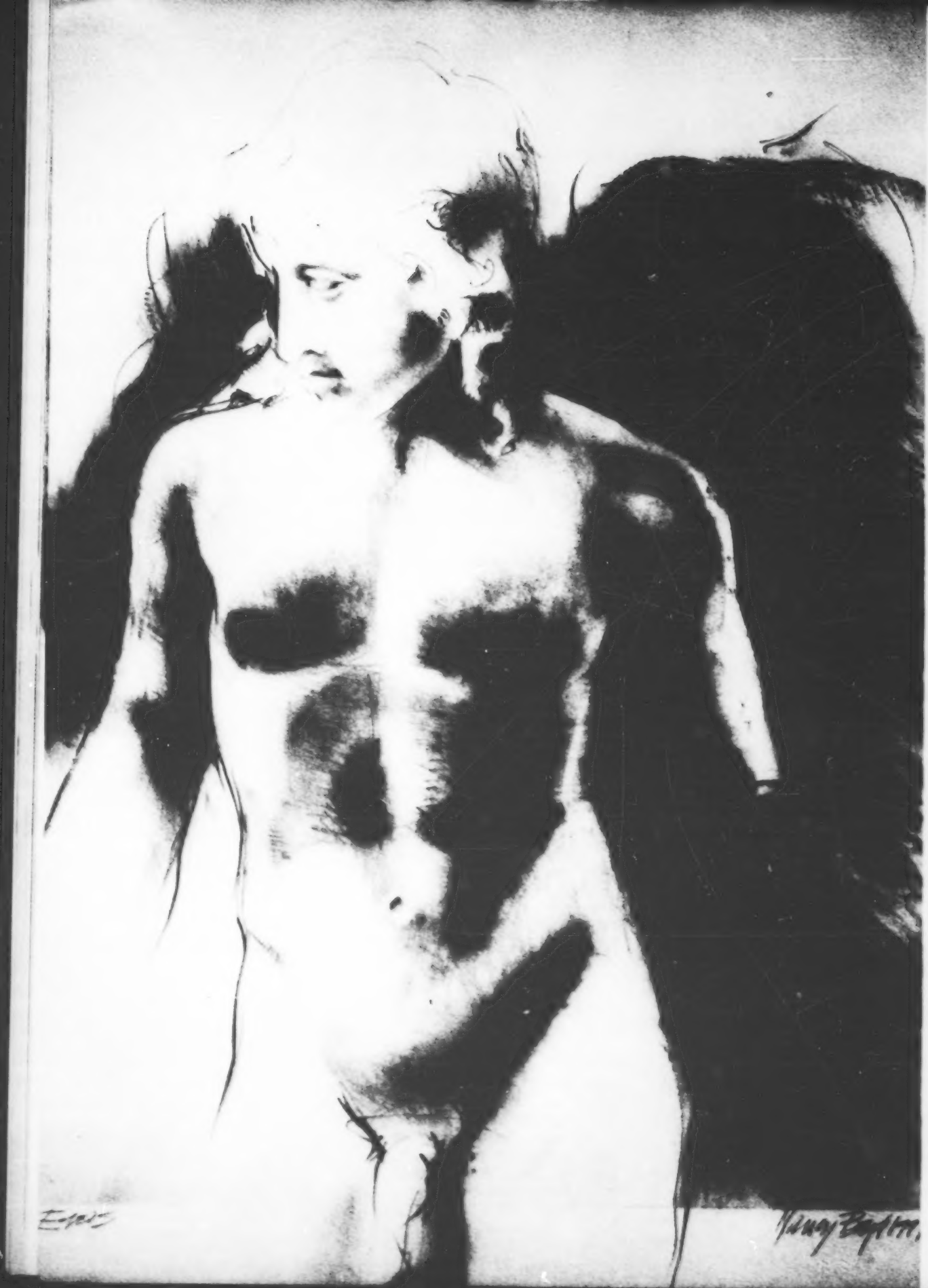
## ASI Fellowships

Tiko Kameda
Pavol Hell
John Bird
Fred Popowich
Slawomir Pilarski
Mike Thewalt
Glenn Chapman
Shawn Stapleton
Menakshinathan Parameswaran
Paul McFetridge

# Faculty Appointments

CSS funding supports more than a dozen full time faculty positions at SFU. The following professor's are supported in whole or in part by the CSS:

Warren Burton, Computing Science
Glenn Chapman, Engineering Science
Arvind Gupta, Computing Science
Robert Hadley, Computing Science
Mehakshinathan Parameswaran, Engineering Science
Slawomir Pilarski, Computing Science
Fred Popowich, Computing Science
Andrew Rawicz, Engineering Science
Tom Shermer, Computing Science
Shawn Stapleton, Engineering Science
Marek Syrzycki, Engineering Science
Peter Triantafillou, Computing Science
Jacques Vaisey, Engineering Science



# Partnerships

As part of its mandate to encourage the application of university research, the CSS encourages partnerships with industry. Such partnerships help professors and graduate students explore new lines of research while sharing the research and development resources of both the university and the corporate partner. The following are just some examples of the industrial partnerships that are emerging at SFU through the CSS.

**3M Canada Ltd.** (Frindt, Morrison)
New materials

**Amoco Production Company** (Burton)
Functional programming and parallel computing

**Bellcore and IBM** (Kirczenow)
Electronic transport properties of semiconductor nanostructures like quantum wires and quantum dots.

**Bell Northern Research**, Ottawa (Stapleton)
High-frequency performance of quantum wells

**Bomem**, Quebec (Thewalt)
Interferrometer applications

**Canadian Cable Labs** (Vaisey)
Video compression technology

**Canadian Space Agency** (Gupta)
Robot arm motion planning.

**Communications Research Center**, Ottawa
(Cuperman)
Speech coding and recognition

(Deen)
Multilevel logic circuits with resonant tunnel diodes

**Crystar Research**, Victoria, B.C. (Thewalt)
Optical characterization of GaAs materials

**CTF Systems Ltd**
(Weinberg)
SQUID-based biomagnetic scanners for study of brain function

(Irwin, Heinrich)
High Temperature superconducting materials

**CTI/Siemans Ltd.** (Atkins, Harrop)
Detectors and algorithms for 3D image reconstruction.

**Department of National Defence** (Bird)
Subsea autonomous vehicles

**Doty Scientific, Inc.** (Jones)
Computer modelling of micro turbine designs

**EG&G**, Quebec (Thewalt)
Optical characterization of materials

**Glenayre**, Vancouver (Stapleton)
64 Kbps digital radio transceiver

**International Submarine Engineering**
(Saif)
Control of hydraulic systems, and fault tolerant control systems

(McFetridge)
Lexical structure for autonomous robot control

(Gupta)
Motion planner for a manipulator arm

**Intertech Systems Inc.** (Leung)
Laser direct-write semicustom chip manufacture

**Kinetic Effects Inc.**, Seattle (Calvert)
Marketing *LifeForms*, SFU developed computer aided choreography software.

**MacDonald, Dettwiler and Associates Ltd.**
(Havens)
Radarsat

(Kameda)
Concurrency control for geographic database systems

(Luk)
Geographic information systems

**McCarney Technologies** (Jones, Havens)
Automobile engine testing &diagnosis expert system

**Microlight Ltd.** (Jones, Havens, Dill)
Intelligent CAD systems

**Moli Energy (1990) Ltd.** (Dahn)
Rechargeable Lithium/Molybdenum batteries

**MPR Teltech**
(Popowich, Havens, Dill)
Intelligent graphic interface to complex real-time systems

(Kameda)
Random testing of VLSI circuits

(Pilarski)
Built-in Self-test of VLSI circuits

(Cuperman)
Speech coding and recognition systems

(Stapleton)
GaAs monolithic microwave ICs

(Thewalt)
Metal organic vapour deposition

**National Institute of Standards and Technology**
(Parameswaran)
Integrated thermal pixels and CMOS compatible micromachining technology

**National Research Council** (DAO), Victoria (Deen)
Electrical and Optical properties of large array CCD's

**Nexus Group** (Cavers, Stapleton)
Mobile satellite power amplifier

**Northern Telecom Electronics**, Ottawa (Deen)
Device modelling, circuit design and noise studies

**Novatel Communications Ltd.**, Calgary
(Cavers, Stapleton)
Next generation cellular phone

**OTEC, Inc.** Huntsville, Alabama (Parameswaran)
Thermal pixel arrays for dynamic thermal scene simulation

**Pacific Microelectronics Center**, Burnaby
(Hobson, Chapman, Krishnamurti))
Large-area restructurable silicon systems.

**PanAbode** (Jones, Havens, Dill)
Intelligent CAD systems

**RANGE VISION INC.** (GUPTA)
3D descriptions from range images

**ROGERS COMMUNICATIONS**
(POPOWICH, CERCONE, MCFETRIDGE)
Natural language database to corporate information systems.

**SIMRAD MESOTECH SYSTEMS LTD.** (BIRD)
Sonar

**TELEDYNE, LOS ANGELES** (STAPLETON)
Next generation air control tower communications

**TEXAS INSTRUMENTS, DALLAS** (DEEN)
Multi-level logic circuits with resonant tunnel diodes

**WEISER INC.** (PAYANDEH)
Fixtures and devices for feeding and holding parts for assembly of locks.

**WESTERN CLINICAL ENGINEERING** (PARAMESWARAN)
Development of applied pressure sensors for biomedical applications

## OTHER COLLABORATIVE PROJECTS

**CWARC** (DAHL)
Collaborating on automatic language translation of agricultural market reports.

**TRIUMF** (HARROP)
Aspects of the design and construction of a new Positron Emmission Tomography (PET) scanner for volume imaging of human brain function.

**INVESTMENT CANADA**
From basic research where university and industry scientists share physical and human resources, to the pre-competitive research stage where concepts and theories are developed into real-world applications, to prototyping of actual products, through to equity/royalty sharing agreements for the final development and marketing of finished products, CSS members are seeking involvement at all levels with industry.

# Research Review 2 Errata

The following information was incorrect or inadvertently omitted from the CSS Research Review 2 of March 1992.

Page 55: Romas Aleliunas is a University Research Associate

Page 57: Veronica Dahl is a Professor of Computing Science

Page 59: Robert Hadley is an Associate Professor of Computing Science

Page 59: Jiawei Han is an Associate Professor of Computing Science

Page 60: Katherine Heinrich is Professor and Chair, Mathematics & Statistics

Page 60: Pavol Hell is a Professor of Computing Science and Mathematics & Statistics

Page 61: Chuck Irwin is a Professor of Physics

Page 62: Wo-Shun Luk is a Professor of Computing Science

Page 62: Christine MacKenzie is an Associate Professor of Kinesiology

Page 63: Ron Marteniuk is Dean of Applied Sciences

Page 64: Andrew Rawicz is an Associate Professor of Engineering Science

Page 65: Ross Saunders is an Associate VP Academic

Page 65: Theodor Sterling is a Professor Emeritus

Page 66: Peter Triantafillou is an Assistant Professor of Computing Science